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The effect of scandium addition on microstructure and mechanical properties of Al–Si–Mg alloy: A multi-refinement modifier

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ABSTRACT

Effect of scandium (Sc) additions on the microstructure, mechanical properties and fracture behavior of Al–Si–Mg casting alloy (F357) were systematically investigated. It was found that Sc addition caused a multi-refining efficiency on the microstructure of as-cast F357 alloy, including refinement of grains and secondary dendrite arm spacing (SDAS), modification of eutectic Si and harmless disposal of β-Al_5FeSi phase. Subsequent T6 heat treatment had further induced the complete spheroidization of eutectic Si and precipitation of fine secondary Al_3Sc dispersoids in the Sc modified alloys. Thus the mechanical properties, especially the ductility, were significantly enhanced by the addition of Sc combined with the heat treatment. The highest ultimate tensile strength, yield strength and elongation were achieved in 0.8 wt.% Sc modified F357 alloy combined with T6 heat treatment. Furthermore, fractographic examinations indicated that the ductile fracture mechanism served as a dominate role in the modified alloys due to the formation of fine, deep and uniformly distributed dimples.

1. Introduction

Al–Si–Mg casting alloys are widely used in automotive and aerospace industries due to their low density, high corrosion resistance and excellent castability [1]. Normally, coarse primary aluminum (α-Al) dendrites, plate-like eutectic Si phases and needle-like Fe-rich intermetallic (e.g. β-Al_5FeSi-phase) are responsible for detrimental effect on the mechanical properties of Al–Si–Mg alloy, especially the ductility. In order to improve the mechanical properties, vigilant improvement efforts have been made to refine coarse α-Al dendrites, modify plate-like eutectic Si and eliminate Fe-rich intermetallic. Grain refinement of Al–Si–Mg alloys is usually achieved by addition of Al–Ti–B and Al–Ti–C system master alloys [2–5]. The modification of eutectic Si is generally carried out by adding modifiers like Na, Sr, and Sb [6–9]. Needle-like Fe-rich intermetallic can be modified to the harmless phase by Be [10] and Mn [11] additions. The addition of minor elements (such as Cu [12]) for supplementary strength through precipitation after the heat treatment is also crucial on the mechanical properties of the mentioned alloys. Thereby, to achieve a combination of the fine grains, modified eutectic Si, harmless disposal of Fe-rich intermetallic and precipitation of nano-sized particles, more micro-alloying elements additions are required. However, the combined additions of the above elements could cause some problems. For example, the combined additions of Sr modifier and Al–Ti–B (or Al–B) grain refiner cause the formation of SrB_6 compound which is difficult to control and could impair the grain refining and Si modifying efficiency [13]. Hence, there is a great interest in searching for single element for achieving the multi-refinement on the microstructures of Al–Si alloy, resulting in a dramatic improvement on the mechanical properties.

Recently, rare earth (RE) elements, such as La [14], Ce [15], Eu [16], Yb [17], and Y [18], have been reported to refine the secondary dendrite arm spacing (SDAS) and modified the plate-like eutectic into a partly fibrous or laminar morphology, inducing considerable improvements on both strength and elongation of the Al–Si alloys. According to the previous studies [19–22], scandium (Sc) has a greater potential for exploring multi-refinement of the microstructures of Al–Si casting alloys. However, there are limited publications about the effect of Sc on mechanical properties of Al–Si casting alloys [23–25], and few detailed observations about the multi-refinement of Sc on the microstructures in Al–Si–Mg casting alloys were carried out. Therefore, in this work, both microstructure and tensile properties of Al–Si–Mg (F357, without beryllium) alloy are symmetrically analyzed to clarify the effects of Sc.

2. Experimental procedure

Al–7 wt.% Si–0.65 wt.% Mg (F357) alloys with different Sc contents were prepared from Al–11.6 wt.% Si–1.1 wt.% Mg and Al–2 wt.% Sc master alloys. The Al–11.6 wt.% Si–1.1 wt.% Mg alloys were melted in an electrical resistance furnace, and then the preheated Al–2 wt.% Sc master alloy was added into the melt at 750 °C. The melt was refined using C_2Cl_6 (0.5 wt.% of the alloy) and then degassed by pure Ar with a

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

Alloys	Si	Mg	Sc	Sr	Impurity				Al
					Fe	Cu	Ti	Others	
F357	6.96	0.61	–	–	0.13	<0.01	<0.01	<0.02	Bal.
F357-0.2Sc	6.94	0.60	0.18	–	0.15	<0.01	<0.01	<0.02	Bal.
F357-0.4Sc	7.08	0.59	0.43	–	0.13	<0.01	<0.01	<0.02	Bal.
F357-0.6Sc	7.04	0.59	0.59	–	0.12	<0.01	<0.01	<0.02	Bal.
F357-0.8Sc	6.96	0.62	0.81	–	0.14	<0.01	<0.01	<0.02	Bal.
F357-0.04Sr	6.97	0.64	–	0.043	0.10	<0.01	<0.01	<0.02	Bal.

constant flow rate of 0.8 L/min for 30 min. After the temperature was down to 720 °C, the melt poured into a metal mold preheated to 220 °C. For comparison, a standard F357 alloy and a 0.04 wt.% Sr modified F357 alloy were also prepared with the same procedure. Chemical composition of the cast ingots were analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES, Thermo Scientific iCAP6300-Radial), and the results are listed in Table 1. A part of the ingots were subject to heat treatment (T6 temper), including solution treatment carried out at 535 °C for 10 h, followed by quenching immediately in the water with temperature of 80 °C, and then artificial aging at 160 °C for 7 h.

Metallographic samples were prepared by standard mechanical polishing and then etched with Keller solution (95 vol.% H_2O, 2.5 vol.%HNO_3, 1.5 vol.% HCl and 1 vol.% HF) for 15 s. In addition, to observed morphology of eutectic Si, some metallographic specimens were etched with 20 vol.% NaOH for 5 min. Carl Zeiss Axio Imager A2m optical microscope (OM) and Carl Zeiss EVO18 scanning electron microscope (SEM) were used to observe the surface morphology. To measure the grain size, the samples were etched with 60 vol.% HCl, 30 vol.% HNO_3, 5 vol.% HF and 5 vol.% H_2O at room temperature for 60 s. The grain sizes of the etched samples were examined using an optical microscope (Carl Zeiss model Axiolab A) and defined according to the following equation [26]:

$$D = 2\sqrt{A/\pi} \quad (1)$$

where A is the average area of the grains, which was also measured using the Image Tool software. For each sample, about 200 grains were measured. The SDAS was measured by linear intercept method [27]:

$$\mathrm{SDAS} = L/n \quad (2)$$

where L is the length of the line drawn from edge to edge of the measured cells and n the number of the dendrite cells. About 50 secondary dendrite arm were measured. The aspect ratio of eutectic Si was calculated based on the average length and width [28]. About 50 particles were measured for each sample. The detailed microstructure of the alloys was further examined by FEI Tecnai G2 transmission electron microscope (TEM). Thin foils of TEM specimens were mechanically ground to the thickness of 60 μm and then ion milled by Res101 machine. Dog-bone shaped tensile specimens with a gauge length of 74 mm and a diameter of ϕ5 mm were machined and polished according to the ASTM E8. standard [29]. Tensile tests were carried out by using Instron 8801 loading frame at a crosshead speed of 0.2 mm/min, and Post-loading fractography was performed via SEM.

3. Results and discussion

3.1. Microstructure observation

The grain refinement performances of Sc and Sr additions on F357 alloy in as-cast condition are shown in Fig. 1. The addition of 0.2 wt.% Sc causes a slight refinement on the grains, as compared with unmodified F357 alloy. With Sc addition increasing to 0.6 wt.%, there is a dramatic decrease on grain size of F357 alloy. The addition of 0.8 wt.% Sc causes a further refinement on microstructure of F357 alloy. However,

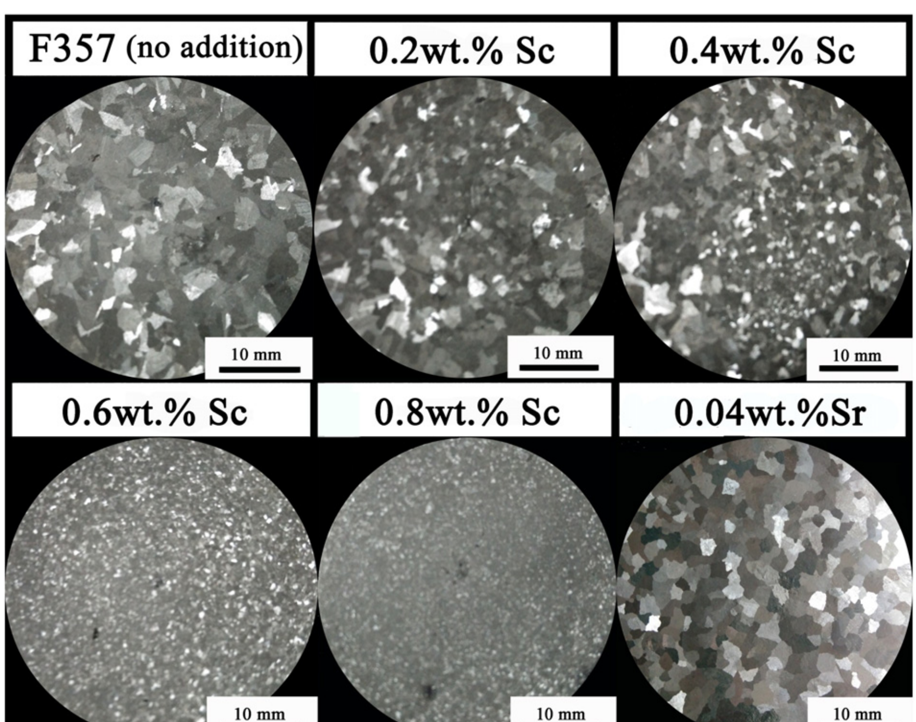

Fig. 1. The grain refinement performance of Sc and Sr additions on F357 as-cast alloy.