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Enhancement of mechanical properties in high silicon gravity cast AlSi9Mg alloy refined by Al3Ti3B master alloy

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ABSTRACT

The microstructure and mechanical properties of high silicon Al9Si0.45Mg alloys without grain refinement and refined by Al5Ti1B and Al3Ti3B master alloys were investigated. The results showed that the primary α–Al grain sizes were 1288 ± 361 μm and 645 ± 146 μm in the non–refined and Al5Ti1B refined alloys respectively, and that was decreased significantly to 326 ± 116 μm in Al3Ti3B refined alloy. After T6 heat treatment, the yield strength, ultimate tensile strength and elongation of the non–refined alloy were 298 ± 2 MPa, 350 ± 2 MPa and 4.5 ± 0.7% separately. When the grain refiner was changed from Al5Ti1B to Al3Ti3B, the yield strength was increased from 304 ± 2 MPa to 311 ± 1 MPa, the ultimate tensile strength was increased from 357 ± 3 MPa to 366 ± 1 MPa, and the elongation was increased significantly by 38.8% from 8.0 ± 1.0% to 11.1 ± 1.2%. The Hall–Petch relation between the yield strength and grain size of the heat–treated alloys was determined as $\sigma_y = 285.1 + 470.2 \cdot d^{-1/2}$. It was found that β" phase was precipitated from the α–Al matrix for the peak strengthening of the heat–treated alloys. TiB_2 and $TiAl_3$ particles were found coexisting in Al5Ti1B master alloy, while TiB_2 and AlB_2 particles were verified coexisting in Al3Ti3B master alloy. The inoculation of AlB_2 particles results in the significant grain refinement under Al3Ti3B. The increase of strength in the Al3Ti3B refined alloy is attributed to the refinement of the primary α–Al grains, while the increase of ductility in the Al3Ti3B refined alloy resulted from the reduced oxides and porosity defects as well as decreased grain size.

1. Introduction

Al–Si–Mg cast alloys have been widely used for making high integrity castings with a combination of good castability, strength, ductility and corrosion resistance [1–3], which are necessary for transport manufacturing to provide light weighting components. The most commonly used Al–Si–Mg cast alloy with good ductility is A356, which contains 6.5–7.5 wt% Si, 0.3–0.45 wt% Mg and provides a yield strength up to 280 MPa [4,5]. However, recent developments in manufacturing lightweight components require the aluminium cast alloys to be able to provide higher strength and also good ductility.

Generally, the strengthening mechanisms in aluminium cast alloys include grain size/grain boundary strengthening, secondary phase strengthening, solution strengthening, precipitate strengthening and strain strengthening. The increase of Si and Mg contents can increase the amount of secondary eutectic Si phase and the Mg_2Si precipitate phase. Therefore, on the basis of A356 alloy, it is expected that the increase of Si level to 9 wt% with the Mg content kept at the up level of 0.45 wt% could offer a higher strength Al–Si–Mg alloy, without obvious decreasing the ductility, since the porosity could be decreased due to the increase of castability. Therefore, it is interesting to study the high silicon Al9Si0.45Mg cast alloys.

Grain refinement has been proved as an important melt treatment during casting aluminium alloys in order to obtain fine primary α–Al grains, which can improve the toughness, strength, formability and machinability [6–9]. Al–Ti–B master alloys, in particular Al5Ti1B, have been widely used as grain refiners over the past several decades [10,11]. The Al5Ti1B master alloy offers a remarkable performance in the casting of wrought alloys, but it is hard to meet the expectations in the case of cast Al–Si alloys, especially with a content of Si higher than 7 wt% [6,12]. The reason is that Si in the melt reacts with Ti to form Ti–Si phases, which poison the TiB_2 nucleation sites and consumes the Ti dissolved in the melt for grain growth restriction [12,13]. Thus the decrease of grain refining efficiency under the commonly used Al5Ti1B master alloy is a severe problem for the high silicon Al9Si0.45Mg cast alloy. One effective method is to reduce the Ti content and increase the B content in the master alloys, and some new master alloys such as Al3Ti3B and Al3Ti1B have been reported, among which Al3Ti3B was found to be able to provide effective grain refinement [14–18]. Therefore, Al3Ti3B master alloy could be considered as a solution to

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Table 1
Chemical compositions of experimental alloys analyzed by ICP–AES (wt%).

Alloy	Si	Mg	Cu	Fe	Mn	Ti	Sr	B	Al
A0 (Al8.3Si0.31Mg)	8.31	0.31	0.00	0.11	0.06	0.130	0.000	0.000	Bal.
A1(Al9Si0.45Mg + No GR)	8.84	0.45	0.00	0.11	0.06	0.130	0.012	0.000	Bal.
A2(Al9Si0.45Mg + Al5Ti1B)	8.80	0.45	0.00	0.11	0.06	0.140	0.012	0.002	Bal.
A3(Al9Si0.45Mg + Al3Ti3B)	8.82	0.45	0.00	0.11	0.06	0.135	0.012	0.006	Bal.

overcome the grain refining problem accompanied with the high silicon Al9Si0.45Mg cast alloy.

The objectives of this paper are to assess the effects of Al5Ti1B and Al3Ti3B grain refiners on the microstructure, and mechanical properties of the high silicon Al9Si0.45Mg cast alloy, to shed a light on the solution of the grain refinement problem accompanied with the high silicon cast aluminium alloy, and provide high strength cast aluminium alloys with high castability, good ductility and excellent corrosion resistance, to meet the increasing requirements in automotive industry.

2. Experimental

2.1. Materials and melt preparation

The base alloy A0, with the composition listed in Table 1 and in the form of ingot, was melted in three 12-kg capacity clay–graphite crucibles separately using an electric resistance furnace. The alloying elements were added to the melt of A0 in order to adjust it to the desired compositions of A1, A2 and A3, as listed in Table 1, where magnesium was added in the pure ingot, and silicon was added in the form of Al–50 wt% Si master alloys. During melting, the temperature of the furnace was controlled at 750 °C, and a melt of 8 kg was prepared in each of the three crucibles. After one hour of homogenisation, Al–10 wt % Sr master alloy was added into the melt to make the defined Sr content of 120 ppm, for modifying the morphology of the eutectic silicon phase during solidification. The melt was subsequently degassed through injecting pure argon into the melt by using a rotary degassing impeller at a speed of 350 rpm for 4 min. After degassing, the top surface of the melt was covered by commercial granular flux, and the melt was hold for 10 min for temperature recovery, followed by casting without grain refinement (GR) using the melt in one crucible, or adding 0.2 wt% Al5Ti1B or 0.2 wt% Al3Ti3B master alloys into the melt in the other two crucibles separately for grain refinement. After adding the grain refiner, the melt was stirred and then hold for 10 min before casting. Mushroom samples were made for composition analysis. The chemical compositions of the alloys were measured by inductively coupled plasma atomic emission spectroscopy (ICP–AES), and the results are listed in Table 1.

2.2. Casting process and heat treatment

With the intention of casting tensile test bars, the prepared melt was poured at 720 °C into a keel block permanent mould preheated at 460 °C, as shown in Fig. 1(a). Fig. 1(b) shows the gravity casting made by the permanent mould, and one round tensile test bar with a size of ϕ20 mm × 166 mm was made from each casting, as indicated by the dashed rectangle box in Fig. 1(b). Eight castings were made one after one in 20 min for each of the non–refined, Al5Ti1B refined and Al3Ti3B refined condition. After kept at ambient condition for at least 24 h, the cast tensile test bars were subjected to T6 heat treatment in an electrical furnace equipped with forced air circulation, including solution treatment and artificial aging. Solution treatment was carried out at 540 °C for 8 h, followed by immediate water quenching to room temperature. Aging treatment was performed at 170 °C for 8 h, followed by air cooling to room temperature. The T6 heat–treated tensile test bars were then machined into the shape shown in Fig. 1(c) for tensile tests, with

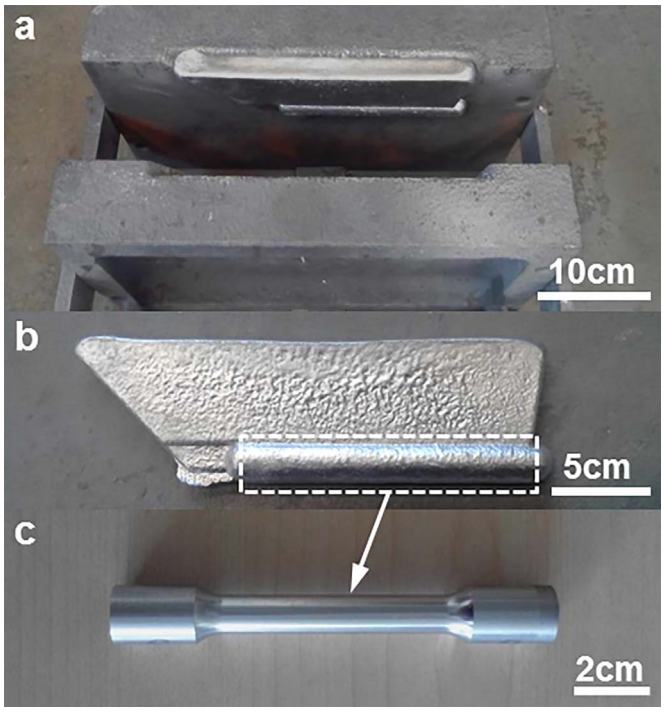

Fig. 1. (a) Keel block permanent casting mould, (b) gravity casting made by the mould and (c) machined tensile test bar from the casting.

the gauge dimension of ϕ10 mm × 50 mm.

2.3. Tensile tests and characterization

Tensile tests were conducted following the ASTM B557 standard using an Instron 5500 Universal Electromechanical Testing System. All the tensile tests were performed at room temperature. The gauge length of the extensometer was 50 mm and the ramp rate for extension was 1 mm/min. Each data reported with standard deviation was based on the mechanical properties obtained from 6 to 8 samples. The microstructure was examined using the Zeiss optical microscopy (OM), the Zeiss SUPRA 35VP scanning electron microscope (SEM) equipped with energy dispersive X-ray spectroscopy (EDS), the JEOL–2100 transmission electron microscopy (TEM) and the D8 X–ray diffraction (XRD) instrument. The specimens for OM, SEM and XRD analysis were prepared by the standard technique of grinding. OM observation was conducted after polishing without any etching. Polarized OM observation of grain size was performed after anodised with Barker solution (97 vol% H_2O and 3 vol% HBF_4). Porosity area percentage was counted from the longitudinal section of three as–cast bars. SEM analysis was conducted after etching with 15 vol% HCl. Post–loading fracture analysis was also performed via SEM. Thin specimens for TEM observation were prepared by standard electropolishing. The electrolytic solution was a mixture of nitric acid and methyl alcohol (2:8), used at –20 to –30 °C and 20 V. TEM operating at 200 kV was used for bright field imaging, select area diffraction pattern (SADP) analysis, and high–resolution transmission electron microscopy (HRTEM) imaging. XRD analysis was conducted from 2 Theta degrees 25° to 100° at a scanning