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Effects of La addition on the microstructure and tensile properties of Al–Si–Cu–Mg casting alloys

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Abstract: The effects of La addition on the microstructure and tensile properties of B-refined and Sr-modified Al−11Si−1.5Cu−0.3Mg casting alloys were investigated. With a trace addition of La (0.05wt%–0.1wt%), the mutual poisoning effect between B and Sr can be neutralized by the formation of LaB_6 rather than SrB_6. By employing a La/B weight ratio of 2:1, uniform microstructures, which are characterized by well refined α-Al grains and adequately modified eutectic Si particles as well as the incorporation of precipitated strengthening intermetallics, are obtained and lead to appreciable tensile properties with an ultimate tensile strength of 270 MPa and elongation of 5.8%.

Keywords: aluminum silicon alloys; rare earth addition; lanthanum; microstructure; tensile properties; precipitates

1. Introduction

Aluminum-silicon casting alloys have wide applications in automotive and power industries because their outstanding castability and low shrinkage can meet the requirements of high complexity and reliability of massive castings [1–3]. Generally, as-cast microstructures of Al–Si alloys are mainly composed of aluminum matrix and eutectic silicon phases. The morphologies of Si phases can be characterized as acicular needles, block-like plates, or refined fibrous structures, which strongly depend on the condition of chemical modification and the cooling rate of castings [4–5]. Alternatively, the mechanical properties of Al–Si casting alloys can be further promoted by introducing trace alloying elements, causing the precipitation of various intermetallic phases during solidification. These precipitated intermetallic phases play an important role for the improvement of tensile properties after heat treatment [6–7]. Magnesium (Mg) and copper (Cu) are the most common alloying elements in Al–Si casting alloys for strengthening, especially with reference to heat treatment [3]. Sjölander and Seifeddine [8] found that, after heat treatment, the tensile strengths of Al–Si–Cu–Mg alloys are much higher than those of the Al–Si–Cu or Al–Si–Mg ternary alloys due to the precipitation of β''-Mg_2Si and θ'-Al_2Cu phases, or Q''-$Al_5Mg_8Si_6Cu_2$ and θ'-Al_2Cu phases, all of which are determined by the content of Cu and Mg. Strontium (Sr), an effective modifier for Al–Si casting alloys, can change the morphology of eutectic silicon phases from acicular to fibrous shape, and distinctly increase the quantity of primary α-Al grains, and thus, both tensile strength and ductility of the alloys can be enhanced [9–10]. Boron (B) has an excellent refining effect on Al–Si casting alloys because the formed AlB_2 particles can act as heterogeneous nuclei for α-Al grains [11–13]. However, Liao and Sun [14] disclosed that a mutual poisoning effect between Sr and B hinders the efficacy of refinement and modification of the microstructures of Al–Si alloys.

Most recently, the influences of rare earth (RE, mainly referring to La or Ce) additives on the modification of Al–Si casting alloys have been reported [15]. By incorporating a proper quantity of RE additives, fine and fibrous eutectic silicon phases can be achieved in the as-cast microstructures, thereby enhancing the tensile strength and ductility of Al–Si alloys. However, the quantity of RE additives required to

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obtain an appropriate modifying effect should be upwards of 1.0wt%, and this can result in the formation of various RE-containing intermetallics, such as RE–23Al–22Si and Al–17RE–12Ti–2Si–2Mg, aggregating at the boundaries of grains or phases, which deteriorates the ductility of Al–Si alloys [16]. On the other hand, Zhu *et al.* [17] found that the precipitated $Al_{11}RE_3$, Al_3RE, and RE-containing intermetallics cannot act as potential heterogeneous nuclei for primary α-Al phases, and suggested that RE addition has no noticeable effect on the refinement of Al–Si alloys. Therefore, the practical applications of RE elements in Al–Si casting alloys are restrained.

The purpose of this study is to investigate the effects of La on the microstructure and tensile properties of as-cast alloys. In the present study, a series of Al–Si alloys containing different La additions were prepared. In addition, 0.05wt% B and 0.03wt% Sr were added into the alloys to ensure sufficient grain refinement and modification. The intermetallic phases derived from the interactions among La, B, and Sr elements were also investigated.

2. Experimental

The chemical compositions of Al–11Si–1.5Cu–0.3Mg alloys with La additions (wt%) of 0, 0.05, 0.1, and 0.2 are listed in Table 1. Commercial pure Al, pure Mg, A413.0 alloy, and Al–8wt%Cu, Al–3wt%B, Al–10wt%Sr, and Al–10wt%La master alloys were used to prepare the designed alloys. The typical procedures employed are as follows. Firstly, pure Al, A413.0 alloy, and Al–8wt%Cu master alloy were melted at (760 ± 5)°C in an electric resistance furnace, and then degassed for 12–15 min by C_2Cl_6. Secondly, pure Mg, Al–3wt%B, and Al–10wt%La master alloys were separately added into the melt at (720 ± 5)°C with slight stirring, and then degassed again. After holding for 15 min, Al–10wt%Sr master alloy was added at (700 ± 5)°C to depress the melting loss. Finally, as the temperature was raised to (720 ± 5)°C, the melt was poured into an ASTM B–108 type permanent mold preheated to (250 ± 5)°C to produce tensile test bars.

Metallographic specimens were sectioned from one of the tensile test bars prior to tensile testing, and an optical microscope (OM, Olympus BX–60M) and scanning electron microscope (SEM, Philips XL30) were employed to analyze the microstructure. The specimens designated for analysis by OM were etched in a 0.5vol% HF reagent for 15 s. Identification of precipitates in the alloys was performed by energy dispersive X-ray spectroscopy (EDS). Tensile testing, implemented according to ASTM standard B557–2002, was carried out at room temperature using an electronic universal testing machine (CMT5105, SANS).

Table 1. Nominal chemical compositions of the experimental alloys wt%

Alloy code	Si	Cu	Mg	Fe	B	Sr	La	Al
AL0	11	1.5	0.3	0.4	0.05	0.03	—	Bal.
AL1	11	1.5	0.3	0.4	0.05	0.03	0.05	Bal.
AL2	11	1.5	0.3	0.4	0.05	0.03	0.10	Bal.
AL3	11	1.5	0.3	0.4	0.05	0.03	0.20	Bal.

3. Results and discussion

3.1. Microstructural characterization

The morphologies of α-Al grains and eutectic Si particles in the as-cast AL0, AL1, AL2, and AL3 alloys are shown in Figs. 1(a, b), 1(c, d), 1(e, f), and 1(g, h), respectively. For the AL0 alloy, the combinative addition of B and Sr elements leads to the presence of well refined equiaxed α-Al grains and fibrous eutectic Si structures (Figs. 1(a) and 1(b)), which is consistent with the results of Ref. [14]. In comparison with the AL0 alloy, an obvious refining effect on α-Al grains and eutectic Si particles can be observed in the AL1 and AL2 alloys with increasing La addition from 0.05wt% to 0.1wt% (Figs. 1(c)–1(f)). However, when the La addition increases to 0.2wt% in the AL3 alloy, both α-Al grains and eutectic Si particles become coarser than those in the AL2 alloy (Figs. 1(g) and 1(h)). The characteristics of α-Al grains observed in the alloys investigated, including aspect and average length, are summarized in Table 2. A total of 10 fields on a cross-section of each specimen were included in the measurements, of which the average values were incorporated into the quantified parameters. Evidently, for α-Al grains, the average size and aspect decrease from 62 μm and 1.8 for the AL0 alloy to 43 μm and 1.4 for the AL2 alloy, whereas both parameters increase to 47 μm and 1.5 for the AL3 alloy, respectively.

The phase compositions identified by XRD patterns and the morphology of precipitated phases in the as-cast microstructures of the Al–11Si–1.5Cu–0.3Mg alloy (AL0) are shown in Figs. 2 and 3, respectively. The Al_2Cu phases are presented as blocky θ-Al_2Cu particles, and the Q-$Al_5Mg_8Si_6Cu_2$ phases form a complex eutectic morphology in the microstructures, being consistent with the observations of Sjölander and Seifeddine [18]. In addition, Fe-containing phases are observed only in the form of β-Al_5FeSi plates (Fig. 3(d)), owing to the relatively high content of Fe (0.4wt.%) in the alloys. Fig. 4 depicts the morphology of intermetallic phases formed in the alloys with different La additions. It can be observed that Sr–B compounds are agglomerated in the La-free AL0 alloy (Fig. 4(a)), which is not evident in the La-doped alloys. The trace addition of La in the AL2 alloy causes the presence of fine La–B compounds, rather than Sr–B compounds, in the center of α-Al grains (Fig. 4(b)). On the other hand, the excessive La addition in the AL3 alloy also causes the precipitation of Al–Si–Sr–La intermetallic phases (Fig. 4(c)).

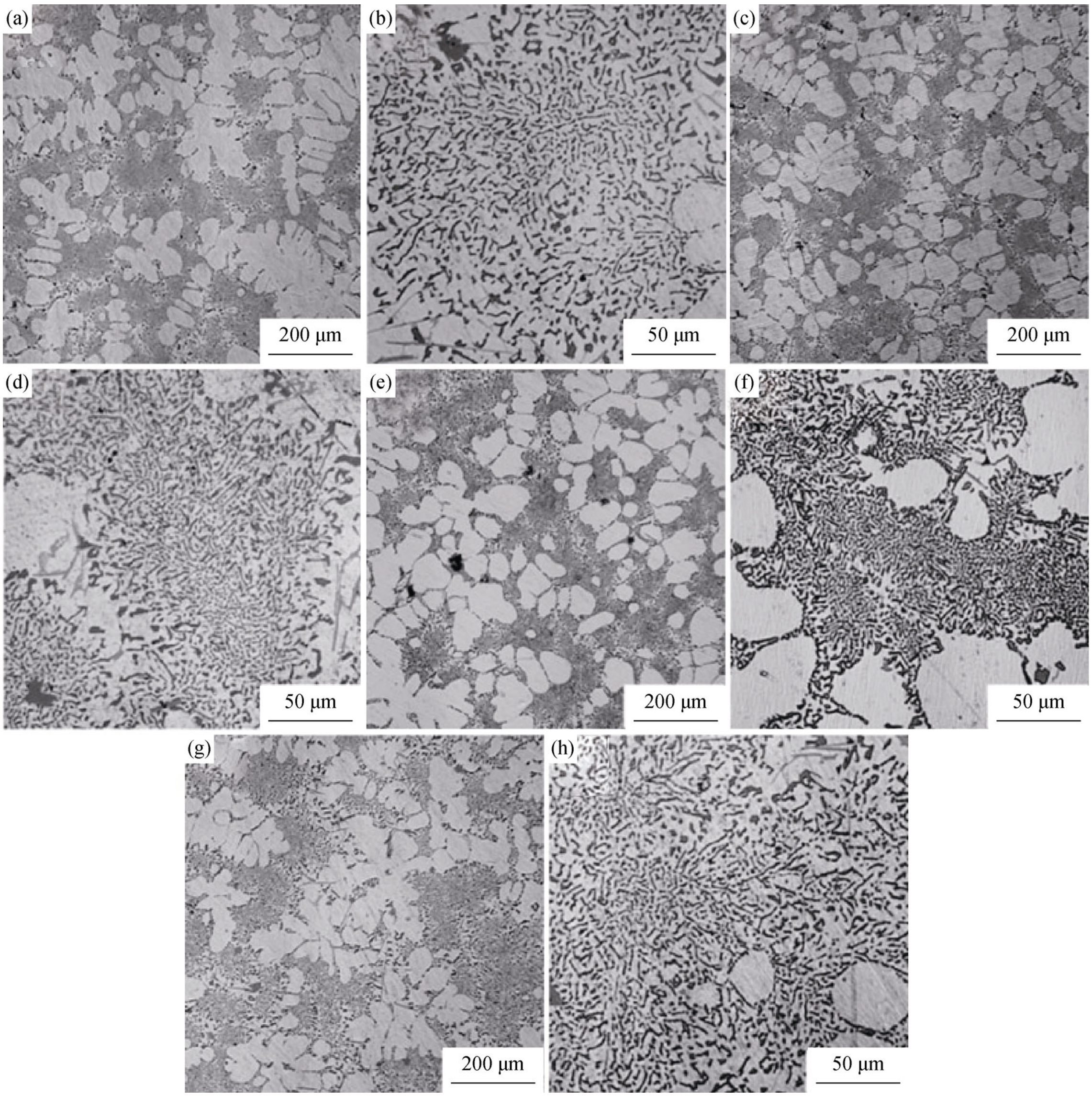

Fig. 1. Microstructures of B-refined and Sr-modified Al–11Si–1.5Cu–0.3Mg alloys with La additions of 0wt% (AL0; a and b), 0.05wt% (AL1; c and d), 0.1wt% (AL2; e and f), and 0.2wt% (AL3; g and h).

Table 2. Characteristics of α-Al grains in the alloys investigated.

Alloy code	Aspect	Length of major axis, L_1 / μm	Length of minor axis, L_2 / μm	Average size, $\sqrt{L_1 \times L_2}$ / μm
AL0	1.82	77.47	49.52	61.94
AL1	1.75	67.92	47.27	56.67
AL2	1.46	49.49	38.27	43.51
AL3	1.54	55.39	40.30	47.24

3.2. Tensile properties

Fig. 5 shows the variations in ultimate tensile strength (UTS) and elongation of B-refined and Sr-modified Al–11Si–1.5Cu–0.3Mg alloys as a function of La content. From the figure, an increasing trend in the tensile strength with increasing La addition from 0 to 0.1wt% is apparent, whereas the UTS value decreases for a La addition of 0.2wt%. An equivalent trend in elongation is also observed from Fig. 5. However, it is worth emphasizing that, for the

AL0 and AL1 alloys, 0.05wt% La addition has no noticeable effect on the elongation. Alternatively, for the AL2 alloy, an appreciable reduction in the size of both α-Al grains and eutectic Si particles leads to the highest UTS value of 270 MPa and elongation of about 5.8% with 0.1wt% La addition.

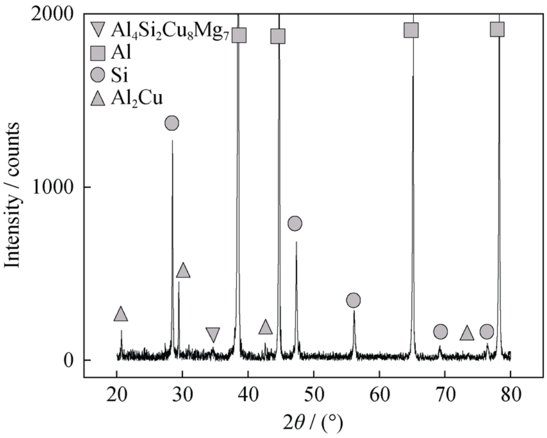

Fig. 2. XRD pattern of the Al–11Si–1.5Cu–0.3Mg alloy (AL0).

3.3. Effects of La addition

In general, the practice of both refinement and modification is believed to achieve superior mechanical properties for Al–Si castings because the finer grain size reduces the size of defects such as microporosity and second-phase particles [19]. Although the Al–3wt%B master alloy, which produces AlB_2 heterogeneous nuclei in the melt, can effectively refine the α-Al grains of Al–Si alloys, particularly if the Si content is above 4wt% [20], the refining efficacy of B has been proven to be hindered by the presence of Sr due to the formation of SrB_6 in Sr-modified Al–Si alloys [21]. Therefore, for the La-free AL0 alloy, the effective quantities of both B and Sr are reduced. This results in the presence of coarser α-Al grains and eutectic Si particles, and lowers the tensile properties relative to the other alloys. A trace addition of La trends to neutralize the mutual poisoning effect between B and Sr by inhibiting the formation of SrB_6 through the formation of LaB_6. This tends to impart a finer grain size and more uniform microstructure for both the AL1 and AL2 alloys by preserving an effective quantity of Sr to ensure a sufficient modification of the eutectic Si particles. Moreover, Li *et al.* [22] has reported that LaB_6 compounds can act as effective and stable heterogeneous nuclei for α-Al grains due to their crystallographic similarities. Therefore, the formation of LaB_6, rather than AlB_2, ensures a greater refining effect resulting in finer equiaxed α-Al grains. However, for the AL3 alloy, excessive LA addition precipitates Al–Si–Sr–La intermetallic phases that reduce the effective quantity of Sr, and thereby impairs the practical effect of the modification of Sr on eutectic Si particles. The

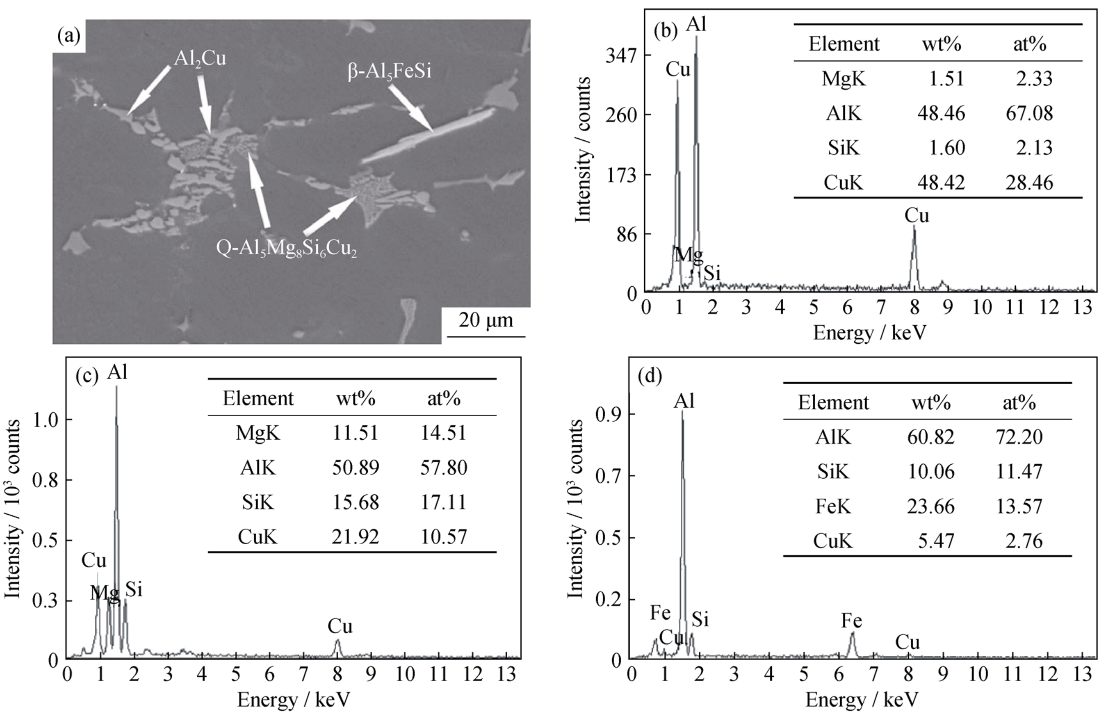

Fig. 3. Morphology (a) and EDS spectra of the θ-Al_2Cu (b), Q-$Al_5Mg8Si_6Cu_2$ (c), and β-Al_5FeSi (d) intermetallics for the Al–11Si–1.5Cu–0.3Mg alloy (AL0).

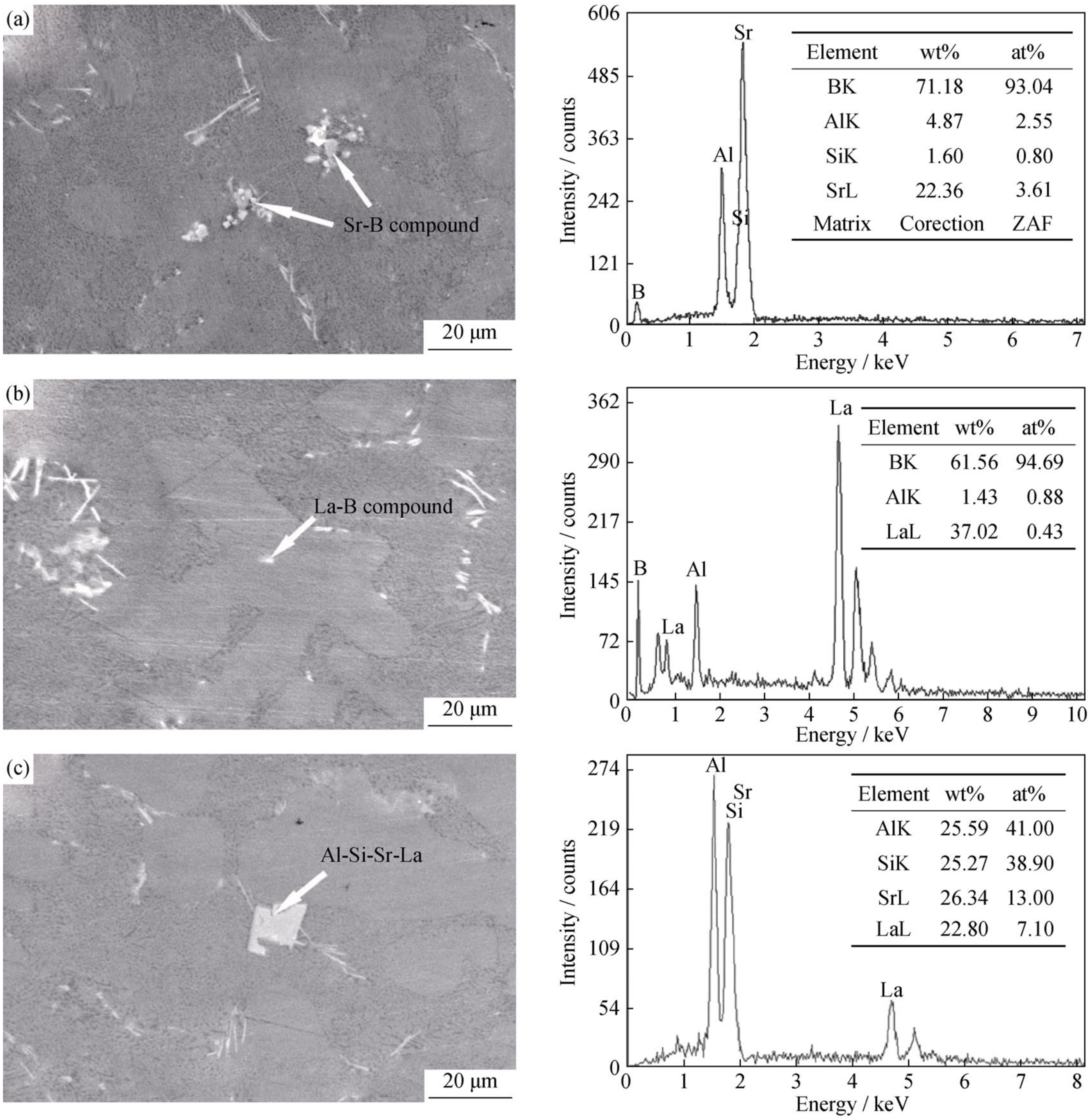

Fig. 4. Morphology and EDS spectra of Sr-B compounds (AL0; a), La-B compounds (AL2; b), and Al–Si–Sr–La compounds (AL3; c).

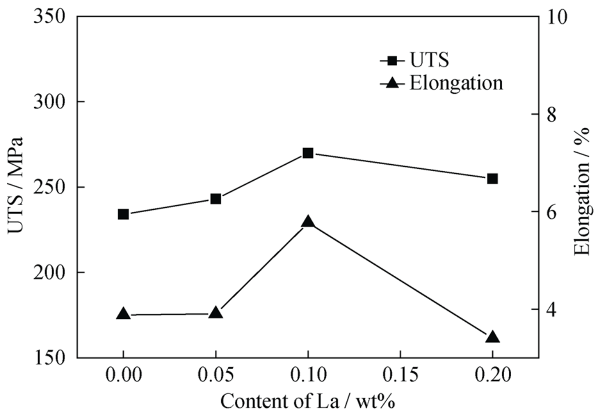

Fig. 5. Ultimate tensile strength (UTS) and elongation of Al–11Si–1.5Cu–0.3Mg alloys with different La additions.

analysis also indicates that an optimized La/B weight ratio (about 2:1 for the AL2 alloy), which favors the formation of LaB_6, can effectively refine the as-cast microstructure. Therefore, controlling the interactions among B, Sr, and La and their effects on microstructure is responsible for the appreciable tensile properties, especially for the promoted elongation, of the AL2 alloy.

4. Conclusions

The influences of La addition on the microstructural characteristics and tensile properties of B-refined and Sr-modified Al–11Si–1.5Cu–0.3Mg alloys have been systematically investigated. The following conclusions can be drawn.

(1) For the La-free AL0 alloy, the practical effects on the refinement of α-Al grains and modification of eutectic Si particles can be hindered by the mutual poisoning effect

between B and Sr because the precipitation of SrB_6 reduces the effective quantities of both elements.

(2) A trace addition of La tends to neutralize the mutual poisoning effect because the presence of LaB_6 not only acts as heterogeneous nuclei for α-Al grains, but also ensures the effective quantity of Sr to obtain sufficient modification of eutectic Si particles.

(3) The optimized La/B weight ratio of 2:1 in the AL2 alloy contributed to the appreciable ultimate tensile strength of 270 MPa, and, in particular, to the promoted elongation of 5.8%. Optimized La addition produced more uniform microstructures composed of well refined α-Al grains and adequately modified eutectic Si particles, and precipitated strengthening intermetallic phases.

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