

Effects of La Addition and Heat Treatment on the Microstructure and Tensile Properties of A357 Aluminum Alloy

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Abstract: This work carried out to investigate the effect of different amounts of La (0.07, 0.1, 0.3 and 0.5) and heat treatment on the microstructures and mechanical properties of A357 alloys. The Microstructure of samples was examined by using optical microscopy (OM). The mechanical properties were investigated by tensile test, and the quality index ($Q.I.=UTS+150*\text{Log}(\text{elongation})$) was used to evaluate the modification efficiency of different La contents. The room temperature tensile test reveals that the addition of La could clearly improve the mechanical properties of alloys which are further improved after heat treatment. Obtained results showed that the addition of La obviously reduced the size and area of eutectic silicon particles after heat treatment. New intermetallics were detected through the microstructural studies at higher La levels. As the amount of La increased up to 0.1 wt%, ultimate tensile strength (UTS) was also increased from 340 MPa to 420 MPa. The addition of 0.1 wt.% La also increased El.% values from 6.2% to 9% in T6 heat treated alloys

Keywords: Aluminum alloy, Rare earth, Casting, Microstructure characteristics.

1. Introduction

Al-Si alloys are the most widely used in foundry industry due to their light weight, excellent mechanical properties and castability. It is well known that magnesium is added to Al-Si alloys for increasing tensile strength. The most popular Mg-containing Al-Si alloys are A356 (Al-7wt.%Si-0.35wt.%Mg) and A357 (with a higher magnesium level). These alloys are featured with excellent casting characteristics, weldability, pressure tightness and corrosion resistance [1].

The mechanical properties of aluminum-silicon cast alloys are mainly related to the chemical composition and microstructure [2,3]. The morphology and size of α -Al primary phase and Al-Si eutectic have significant effects on mechanical properties of Al-Si cast alloys. Tensile properties of the Al-Si cast alloys, especially in the ductility, are mainly controlled by the dendrite cell size of α -Al primary phase. Moreover, the eutectic silicon particles also play an important role in the fracture behavior and tensile ductility of Al-Si cast alloys [4]. Ductility, fatigue and tensile strength are limited by the dendritic structure and non-uniform distribution of acicular Si particles [5]. Chemical modification is regarded as a low price and effective modification method for improving the morphology and size of α -Al primary phase and eutectic silicon particles. Generally, many chemical elements are known to be used for chemical modification method, such as Ti, B, Sr, Na, Sb and rare earth(RE) elements including Ce, La, Yb, Eu and Sc [6–9]. RE elements containing La not only can refine α -Al primary phase, but also can modify eutectic silicon particles [10]. Further investigation by the use of an appropriate solution treatment can modify the morphology of eutectic silicon particles. T6 heat treatment, including solid solution strengthening and then precipitation of the fine coherent particles inside the microstructure during the aging process, has been used to improve the mechanical properties of the alloy. T6 treatment comprises solutionizing at a relatively high temperatures (530-550 °C), then quenching in water and finally artificial (155-210 °C) [11-13].

In this study, different amounts of La (0.07, 0.1, 0.3 and 0.5) were added into A357 Al-Si alloy to investigate its effect on the microstructural characteristics, tensile properties and fracture behavior of A357 thin section castings after T6 heat treatment.

2. Experimental procedure

Pure Al (99.8%), Si (99.5%) and Mg (99.9%) were used to produce primary A357 ingots, in the beginning of this work. After melting Al in a 10 Kg graphite crucible via an electrical resistance furnace and heating up to 800 °C, Si and Mg were added into the molten Al to prepare A357 alloy. The chemical composition of A357 primary ingots prepared in this study is shown in Table 1.

TABLE I: Chemical composition of A357 Casting alloy

Alloy	Si (wt. %)	Mg (wt. %)	Fe (wt. %)	Cu (wt. %)	Mn (wt. %)	Zn (wt. %)	Al (wt. %)
A357	7.20	0.49	0.09	< 0.01	< 0.01	< 0.01	Base

Then, remelting of chopped primary ingots was carried out in a small SiC crucible (1 Kg capacity). When the temperature reached 780 °C, Al-20 wt.% La master alloy was added into the melt to obtain different amounts of La (0.07, 0.1, 0.3, 0.5) in the alloy. In each trial, Al-20 wt.% La master alloy was added into the remelted alloy, held for about 10 min in the molten metal. Before stirring and cleaning off the dross and pouring, the melts was stirred manually with a graphite rod for about 1min to ensure complete mixing. Alloys with different compositions were poured into a preheated cast iron mould (280 °C). This mould was made according to the B108-03a ASTM standard (Fig.1a). Specimens were subjected to T6 treatment. For this purpose, they were solution treated in an accurate electrical furnace at 540 °C for 8 h, then quenched in water to room temperature and finally, aged in 170 °C for 7 h prior to air cooling. For structural studies, the specimens were selected from the gauge length portion of the test bars (with 6 mm diameter), as seen in Fig.1b. Metallographic specimens were ground, polished according to the standard metallographic procedure and etched by HF (5%) to reveal the microstructure. Microstructural parameters were determined using an optical microscope equipped with an image analysis system (Clemex Vision Pro. Ver. 3.5.025). The microstructural characteristics of the specimens were also examined by SEM performed in a Vega©Tescan SEM+. Phase identification was also performed by x-ray diffraction (XRD), using PHILIPS binary diffractometer and applying Cu- α radiation. Tensile test specimens were prepared according to ASTM B557M-10 standard, as seen in Fig. 1b. Tensile testing was carried out by a computerized testing machine (SANTAM STM-20) at the constant cross-head speed of 1 mm/min at room temperature.

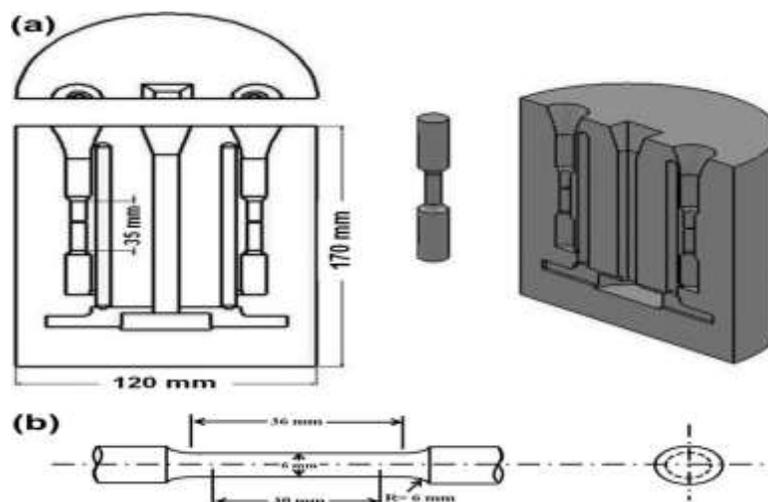


Fig. 1: (a) Cast iron mould and (b) tensile samples dimensions

Fracture surface characterization studies were carried out on the tensile fractured samples in order to provide valuable insight into the various fracture mechanisms operative during tensile loading. Fracture surface characterization studies were primarily accomplished using similar SEM.

3. Results and Discussion

3.1. Microstructural Characterization

The microstructure of the as-cast A357 alloy is shown in Fig. 2(a). The as-cast microstructure consists of aluminum rich dendrites separated by the eutectic silicon particles. With T6 heat treatment of 8h at 540 °C, spheroidisation of the silicon particles (black rounded particles) is observed (Fig. 2(b)).

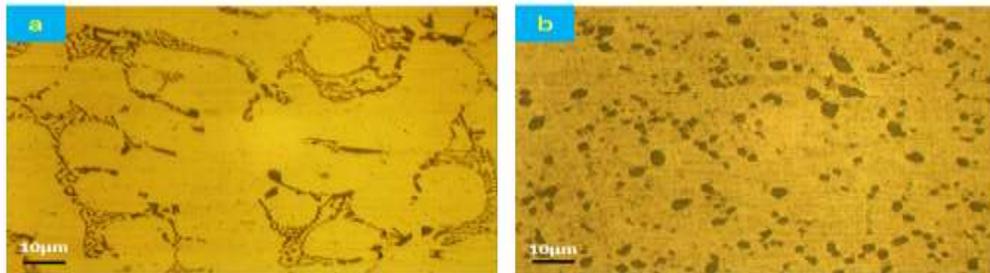


Fig. 2: Microstructures of (a) as-cast ingot A357 alloy and (b) T6 heat-treated cast ingot A357 alloy

The optical micrographs of A357 alloys with different La contents in T6-heat treated conditions are shown in Fig. 3.

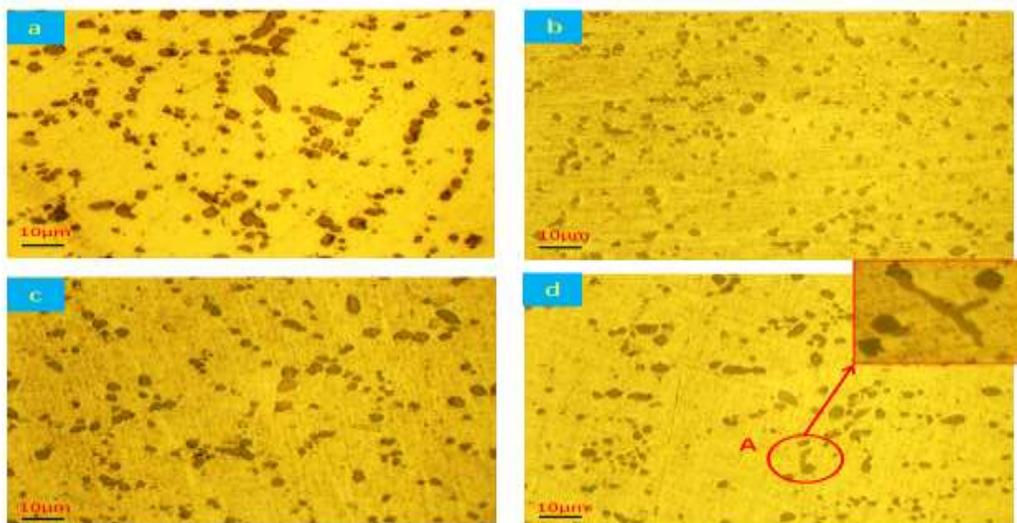


Fig. 3: The microstructures of A357 alloys with different concentrations of La in T6-heat treated conditions (a) 0.07wt% La; (b) 0.1wt% La; (c) 0.3wt% La; (d) 0.5wt% La addition

From Fig. 3 and Tables 2, it can be seen that the addition of La reduces the particle length and area of Si particles. It is obvious that T6 heat treatment has a profound effect on the spheroidization of eutectic Si, especially in the La added alloys. The maximum reductions in particle length, area and the aspect ratio of the heat treated samples by the addition of La are 37%, 58% and 16%, respectively.

TABLE II: Si particle characteristics of various A357 alloy samples

Sample (Heat treated)	La (wt%)	particle length (µm)	particle area (µm ²)	Aspect ratio (%)
LH0	0	9.3±0.4	11.5±3.2	2±0.2
LH0.1	0.1	5.9±0.3	4.8±0.5	1.7±0.1
LH0.5	0.5	8.4±0.4	9.8±3.3	1.7±0.3

As shown in Fig 3a-d, silicon particles are spheroidized in eutectic area after T6 heat treatment. As for the modified alloy, the size of Si particles are clearly smaller than that in the unmodified alloys due to the effect of

La on the initial size and area of eutectic silicon particles, but the addition of more La (>1 wt.%) does not lead to much reduction in the size and area of eutectic silicon particles. It has been also reported that the addition of La reduces the coarsening of the eutectic silicon particles during solution heat treatment [2,10]

For the reason that initial size of eutectic silicon particles mostly controlled the spheroidization efficiency of eutectic silicon particles [2,10], so they are clearly spheroidized and homogenously distributed in the grain boundary after T6 heat treatment.

According to an impurity induced twinning modified Si fibers include more twins than the unmodified ones and have a rough microfaceted surface and each surface imperfection is a potential site for branching. Therefore, the silicon fibers are tend to bend, curve and split in the chemically modified eutectic to create a fine microstructure. Lu and Hellawell [14] believe that a growth twin is generated at the interface when the atomic radius of the element has the accurate size relative to the radius of Si (relement:rsi = 1.65). Tsai et al. have also mentioned that La element is found to be in the atomic radius range proposed to cause chemical modification [15].

However, adding higher amount of La is expected to introduce large intermetallic compounds, which has been shown by A in Fig. 3d. The XRD patterns of A357-3 wt.% La alloy shows intermetallics (as shown in Fig. 4). Fig. 5 also shows the morphology of La intermetallic. Jiang et al. [10] showed that the intermetallic compounds have a very high melting point and the lattices constant of the intermetallic compounds are similar with α -Al. consequently, the intermetallic compounds can also supply some nucleation cores for the α -Al primary phase and SDAS are decreased because of the large number of nucleation cores in the Al liquid. As a consequence, the morphology and size of α -Al primary phase and eutectic silicon particles are improved with the addition of La [10].

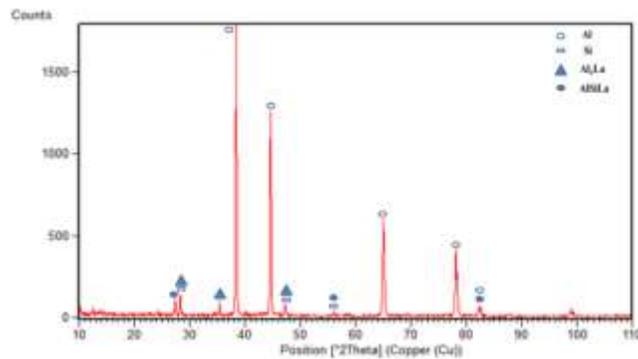


Fig. 4: XRD patterns of A357 alloy specimen with 3 wt.% La

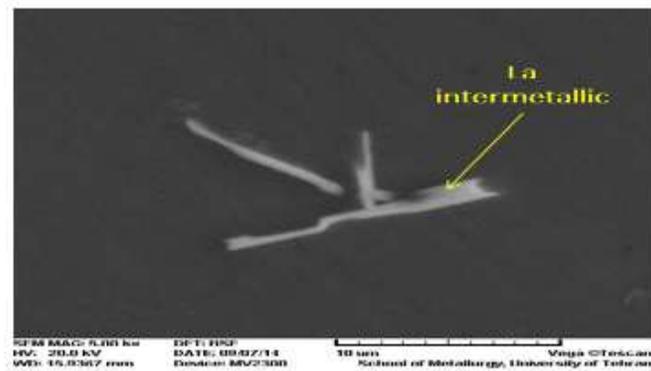


Fig. 5: SEM of A357 containing 0.5wt.% La

3.2. Tensile Properties

The variation of UTS and elongation values after adding La to the A357 alloy in the T6 conditions, as seen in Fig. 6

It is evident from Fig. 6a, the addition of 0.1 wt.% improves Ultimate tensile strength values of the alloy from 340 MPa to 420 MPa, which is in agreement with the results obtained from microstructural observations.

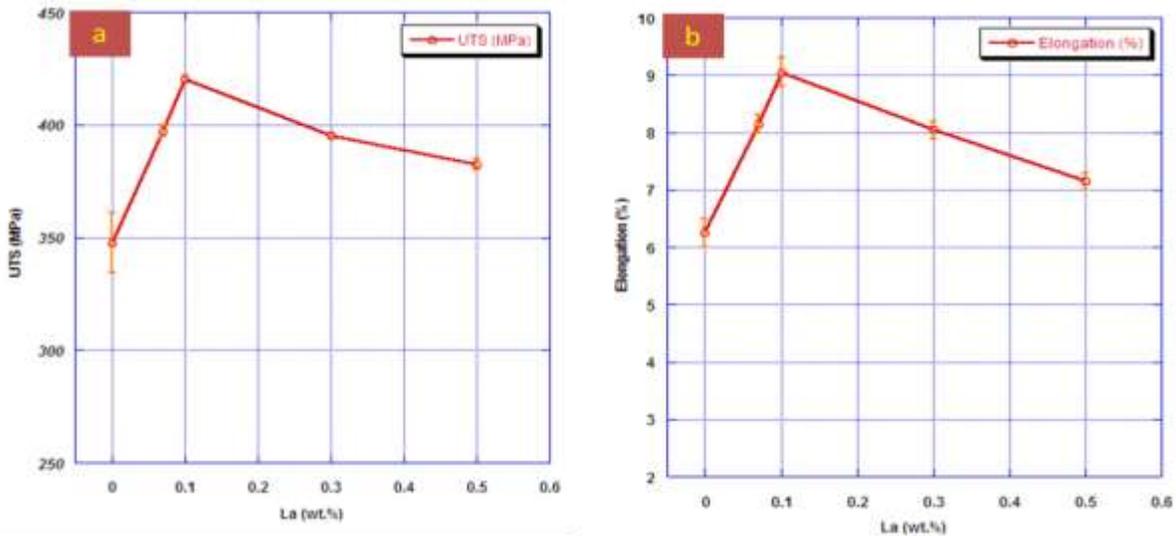


Fig. 6: (a) UTS and (b) elongation values of A357 alloy as a function of La content in T6 heat-treated conditions

Also, it can be noted that the presence of eutectic silicon particles with globular structure (shown in Fig.3) are barriers for dislocations movement, consequently, every dislocation gliding over the slip plane adds one loop around the particle. These loops exert a back stress on dislocation source which must be overcome for additional slip to take place. This leads to an increase in strength in T6 heat-treated [16,17], but the added of higher La concentration (more than 0.1 wt.%) cause a significant reduction of UTS values the formation of an intermetallic phase (AlSiLa) with flake morphology, as shown in Fig.5 ,may lead to high levels of stress concentration which provide appropriate sites for crack nucleation and therefore the reduction of tensile properties.

From Fig. 6b, it is evident that addition of 0.1 wt.% La to the alloy increases the EL.% values from 6.2% to 9% in T6 heat treated alloys. But, in the higher contents of La (more than 0.1 wt.%), as shown in Fig. 6b, elongation value has a decrement from 9% to 7%. The formation of a new intermetallic phase (AlSiLa) with acicular morphology can cause deleterious effect on the elongation [2]. It was reported that a trace amount of rare earth elements could change the rupture mechanism of aluminum alloy, and the transgranular/intergranular mixed mode can be observed [2,10].

To quantify the overall tensile properties of an alloy the quality index (Q.I.) which is defined as $Q.I. = UTS + \alpha * \text{Log} (\text{El. } \%)$ was utilized, where α is 150 for Al-Si-Mg alloy [2, 18,19]. This concept arose from the combination of UTS and elongation values are a reliable parameter in quantifying tensile properties for engineering applications. It is much more descriptive of the true tensile properties of castings than either the tensile strength or the elongation alone. The quality index Q.I. evaluated for each alloy is also shown in Fig. 7.

Fig. 7 clearly shows that the addition of 0.1 wt.% La lead to an enhancement the quality index from 467 MPa to 561 MPa after T6 treatment.

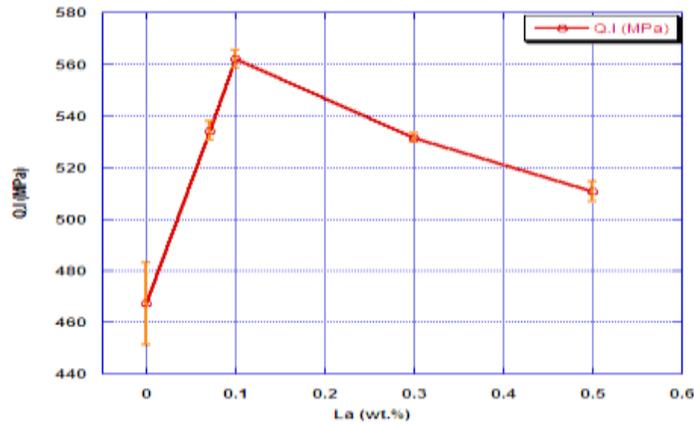


Fig. 7: Quality Index values of T6 heat-treated conditions, as a function of La concentration

3.3. Fracture characteristic

Fig. 8 demonstrates the fracture surfaces of the A357 alloy containing 0, 0.1 and 1 wt.% La under T6 heat treatment conditions.

After T6 heat treatment few dimples can show in the fracture surface of the A357 unmodified alloy. The fractures displayed by the samples containing La have more ductile behavior compared to brittle made of the unmodified. Also some investigator have reported that La addition to A357 alloy converts the fracture behavior from brittle, with quasi-cleavage facets to ductile, with fine dimples [2,10] Fig. 15 c exhibits the fracture surface at higher La contents (about 1 wt.%) the presence of La-rich intermetallics plays an important role in changing the fracture behavior from ductile to brittle [2,10]. Aggregation of these brittle intermetallic compounds can make potential sites for stress concentration resulting in a significant deterioration of elongation.

It is noted that applying T6 heat treatment obviously much more ductile fracture

Alexopoulos et al. [20] were observed the mechanism of void growth and coalescence at the Si particles they also noted that when the silicon particles become spherical and small the intergranular fracture are happened. It was reported that a trace amount of rare earth elements could change the rupture mechanism of aluminum alloy, and the transgranular/intergranular mixed mode can be observed [2,10].

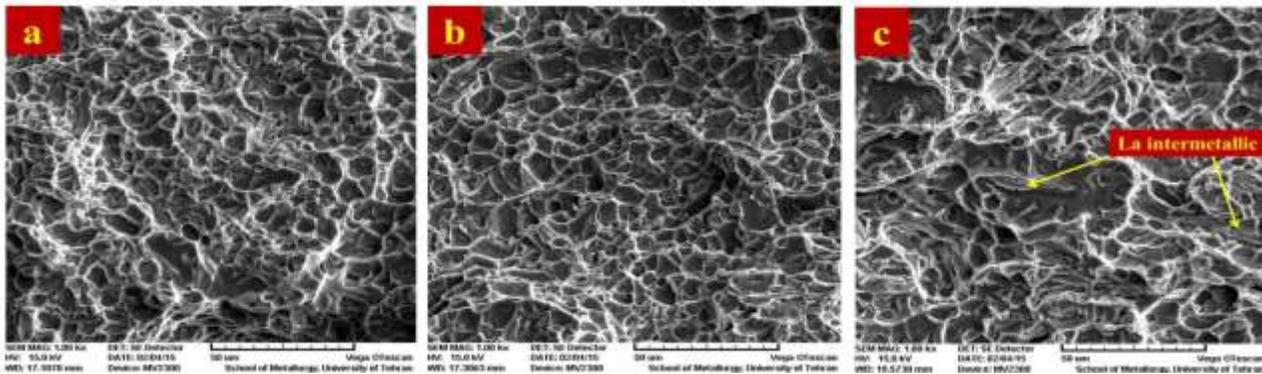


Fig. 8: SEM micrographs of fractured surfaces of 357 alloy after T6 heat treatment (a) without La, (b) with 0.1% La and (c) with 1% La

4. Conclusions

The effects of different La contents on the microstructure and tensile properties of heat treated A357 Al-Si alloy were investigated. The following conclusions can be drawn:

1. The addition of La greatly reduced the size of eutectic silicon particles. A new intermetallic phase found in the microstructures of the modified alloy with higher La contents (≥ 0.1 wt. %).
2. It was found that the addition of La improved the tensile properties of A357 alloy compared to the unmodified A357 alloys. T6 heat treatment has a marginal effect on tensile properties of the modified and non-modified alloy significantly, Also, fractured surface after T6-heat treatment show fine dimples which are the characteristics of the ductile mode of fracture.

5. Acknowledgements

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