The Effect of La-Intermetallic Compounds on Tensile Properties of Al-15%Mg$_2$Si In-Situ Composite

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Abstract

In this work, an attempt was made to examine the effect of different La-intermetallic on the microstructure and tensile properties of Al-15%Mg$_2$Si metal matrix composite (MMC). The composite was made via in-situ process and characterized by optical microscope (OM), scanning electron microscope (SEM) equipped with energy dispersive X-ray spectroscopy (EDX) and X-ray diffraction (XRD) analysis. Microstructural characterization revealed that La changes not only the morphology of primary Mg$_2$Si particles from irregular to polyhedral and cubic shape. But also alter the eutectic Mg$_2$Si phase from flakes to rods and the volume fraction of Mg$_2$Si decreases while volume fraction of α-Al phase increases. La addition change the size of primary Mg$_2$Si from (~17 μm) to (~10 μm) and the size of eutectic Mg$_2$Si phase is reduced from more than 4.0 μm to less than 0.5 μm. This is mainly due to the formation of LaSi$_2$ phase during solidification, as detected by XRD analysis. Further results revealed that as the amount of fine La-intermetallic is increased, ultimate tensile strength (UTS) and elongation values of the MMC were also significantly increased. The fracture study of the composite showed the La-intermetallic changes the mode of fracture from brittle to more ductile.

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1. Introduction

Today, the fuel consumption and pollutants entering the environment is taken into consideration. That's why weight loss is an important factor in reducing fuel consumption in car and aerospace industry has provided a variety of research fields, Henry et al. (2003), Yang et al. (2011). Aluminum has low weight and it is suitable for use as matrix in metal matrix composites, Among composite materials, aluminum matrix composite reinforced with Mg2Si particles are increasingly developing due to their favorable properties such as low density, excellent casting ability, good wear resistance and low prices of final products. Mg2Si is a hard intermetallic compound with a high melting point (1085 °C), its low density and low coefficient of thermal expansion coupled with a reasonable high elastic modulus make it a good choice as a reinforcing agent, Zhang et al. (1999). Zhang showed that in terms of properties and solidification behavior, great similarities exist between Mg2Si and Si, and between Al–Mg2Si and Al–Si systems. Fig. 1 shows the equilibrium phase diagram of Al–Mg2Si, Zhang et al. (2000). It can be seen that during solidification of Al-15%Mg2Si alloy, Mg2Si phase is formed as the primary phase. Then, α-Al and secondary Mg2Si co-solidify from the liquid alloy in the narrow ternary phase area. This pseudo-eutectic reaction is completed at 583.5 °C, Emamy et al. (2010).

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L \rightarrow L_1 + Mg_2SiP \rightarrow Mg_2SiP + (Al + Mg_2Si) E \text{ where } E \text{ is a Eutectic, P is a Primary, and } L_1 \text{ is a Liquid in two phase region.}
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In situ process of fabricating metal matrix composites (MMCs) has some benefits, such as uniform distribution of reinforcement, well matrix–reinforcement interface, thermodynamically stable system and much lower costs of production as compared with their counterparts from ex situ processes, Bahrami et al. (2012). Unfortunately, primary Mg2Si phase composites are usually coarse, which resulted in the loss of mechanical properties. It is therefore necessary to be refined by adding alloying elements such as Na, Emamy et al. (2011), Ce, Zhou et al. (2005), Sr, Qin et al. (2007), Ti, Li et al. (2008). The aim of this research is the study of La addition as a modifier to improve the mechanical properties of Al-15%Mg2Si composite.

2. Experimental

Industrially pure Al (>99.8% purity), Mg and Si metals were used to prepare Al–5.5 wt. %Si–9.7 wt. %Mg alloy. Al–15%Mg2Si composite as primary ingots were prepared in an electrical resistance furnace using a 10 kg SiC crucible. The parent alloy was remelted within a small SiC crucible (with 1 kg capacity) in a resistance furnace in order to prepare alloys with 0, 0.05, 0.1, 0.3, 0.5, 1, 2, and 3 wt % La. When the temperature reached 760 °C, Al-15%La containing master alloy was added to the molten composite. After cleaning off the slag, alloys with different compositions were poured into a preheated cast iron mold (up to 200 °C) to produce tensile test specimens (Fig. 2).

The mold was prepared according to ASTM B108/ B108M-12e1 (Fig. 2). The main advantage of this mold is the application of an appropriate uphill filling system and feeding design, providing a low turbulence manner of fluid flow which consequently results in reduced gas entrapment and porosity in cast specimens. The size of tensile test specimens considered for the mentioned mold was consistent to ASTM B557M-10 standard, as shown in Fig. 2. Microstructural studies were made on polished sample surfaces which were selected from the gauge length portion of the test bars (6 mm diameter) (Fig. 2b). The cut sections were polished and then etched by HF (5%) for about 10s at
room temperature to reveal the structure. Quantitative data on the microstructures were determined using an optical microscope and were analysed with image analysis software (Digimizer). The microstructural characteristics of the specimens were examined by scanning electron microscopy performed in a Vega©Tescan SEM equipped with the energy dispersive X-ray analysis (EDX) accessory. Tensile test was carried out on a computerized testing machine (Santam STM-20) at room temperature to obtain UTS and elongation values at a strain rate of 1 mm/min. The fracture surfaces of tensile test specimens were also examined with SEM.

3. Results and discussion

3.1. Microstructural characterization

In the microstructure of Al–15% Mg$_2$Si composite, according to the pseudo-binary phase diagram (Fig. 1), Zhang et al. (2000), consists of dark faceted particles of primary Mg$_2$Si and bright α-Al grains in a matrix of Al–Mg$_2$Si eutectic cells. Consequently, primary Mg$_2$Si particles will act naturally as heterogeneous sites for the nucleation of α-Al in order to decrease the interfacial energy, Zhang et al. (1999). This explains why all Mg$_2$Si particles are surrounded by a layer of α-Al, as seen in Fig.3. Fig. 3a–f related to the addition of La values (0% to 3%). As is clear from the Fig. 3, with the addition of the different amounts of La, the microstructural changes were found to be associated with the formation of new intermetallic phase. To recognize this intermetallic, XRD analysis of the samples containing 5% La was redirected.

Figure 4 clearly shows the XRD patterns of the composite after adding 5% La. These observations can clearly shows the effect of LaSi$_2$ phase on the microstructure of the composite. The presence of LaSi$_2$ phase has been also reported by Yang et al. (2000).
Fig. 4. (a) XRD patterns of Al–15%Mg2Si composite with 5% La additions; (b) SEM micrograph of the Al–15%Mg2Si–5%La composite.

As expected, the size and shape of these phases will have a direct impact on microstructure and tensile properties. From Fig. 3a, it is clear that the morphology of primary particles Mg2Si in Al-15%Mg2Si composite is almost dendritic or irregular shape but with added La, it changes to polyhedral and cubic shape (Fig. 3(c-f)). Also, it seems that with increasing La, the α-Al phase volume fraction is increased. Another important change occurs in eutectic area Mg2Si. With increasing La content (wt %), the morphology of Mg2Si eutectic alters from flake like to fiber or dot like. Further microstructural studies depicted that the size of Mg2Si eutectic is changed from 4 μm at 0.3 % La addition to less than 0.5 μm at 1 % La (Fig. 5). Investigation on the size and volume fraction percent of primary Mg2Si particles is shown in Fig. 6a. The results showed that the size of primary Mg2Si particles when 0.5% added La to composite is 17 μm but 3 wt % La additions reduces the size of primary Mg2Si particles to 10 μm. Also, with the addition of various amounts of La the volume fraction percent of primary and eutectic Mg2Si is steadily declining. It is clear that La at lower content modifies the Mg2Si phases but at higher contents, it tends to react with Si to form La containing intermetallics.

Fig. 5. SEM micrograph of Al-15%Mg2Si composite with different amount La for explains different size of Mg2Si eutectic (a) 0.3%; (b) 1 %.

3.2. Tensile properties

The UTS and elongation values of the specimens as a function of added La are shown in Fig. 6b. As is clear from Fig. 7b that both UTS and elongation value are decreased for MMCs with less than 0.3 wt % La but when the amount of La is greater than 0.3% an increase in tensile properties is observed. This result in the form intermetallic compounds containing La and their effects linked. In MMC with 0.3% La, the intermetallic compounds have needle shape and increase in stress concentration is expected which leads to the loss of strength. But La at higher values (0.3%), the shape of such intermetallic changes from needle to flake/fiber shape. On the other hand, the size of Mg2Si primary particles is smaller and the morphology of eutectic Mg2Si is changed from flake like to fiber and dot-like shape that
these results are the main reason for increased UTS value. About change in the percent elongation, it can be argued that up 0.3 % of La added, the formation of intermetallic phase’s needles shape damaging effect on the elongation value but in amounts greater than 0.3% La, to form LaSi2 phase, increasingly more silicon used so the phase matrix $\alpha$-Al is increased that obviously, these results will increase the percentage of elongation.

![Fig. 6](image_url) (a) The size and volume fraction of primary Mg$_2$Si particles as a function of La additions; (b) Tensile properties of Al–15%Mg$_2$Si MMC as a function of La content.

### 3.3. Fractography

Fracture surfaces of the unmodified and La. modified Al–15% Mg$_2$Si composite are shown in fig7 (a-b).

![Fig. 7](image_url) (a) La-free Al–15%Mg$_2$Si MMC; (b) Al–15%Mg$_2$Si–2%La MMC.

As fig. 7a depicts, fracture surfaces of the unmodified Al–15% Mg$_2$Si composite have very decohered primary Mg$_2$Si and density of fine dimples on their fractured faces are low which indicates brittle fracture. The fracture planes for almost all coarse Mg$_2$Si particles exhibit clear cleavage characteristic creating a rapid fracture deriving from their intrinsic brittleness. As known, dimples with honeycomb appearance are characteristics of a ductile mode of fracture. Fracture surface in fig. 7b depicts that modified composite with 2wt% La contains several cracked particles and fine dimples accompanied by a few decohered primary Mg$_2$Si particles. As previously mentioned, with increasing the amounts of La, silicon is expected to be used at the same time and thus the volume fraction Mg$_2$Si primary and eutectic Mg$_2$Si structure is decreases. So the volume fraction of $\alpha$-Al matrix is increased. As a result, percent elongation increases and the fracture mode convert from brittle to ductile.
4. Conclusions

- The morphology of primary Mg$_2$Si changed from irregular to polyhedral and cubic shape and its average particle size decreased from 17 $\mu$m to 10 $\mu$m after adding La to Al-15% Mg$_2$Si composite.
- With the addition of La to Al-15% Mg$_2$Si composite and formation LaSi$_2$, the volume fraction of Mg$_2$Si particles and eutectic is decreased but alpha phase is increased.
- Size of eutectic Mg$_2$Si phase is reduced from about more than 4 $\mu$m to less than 0.5 $\mu$m after adding 1%La to Al-15% Mg$_2$Si composite.
- With the addition of 0.3% La, UTS is decreased from 217 to 199 MPa and elongation values decreased from 5.5 to 4.2%, but after adding 3%La, UTS is increased to 223 MPa and elongation values increased to 6%.
- The fracture surface examinations of the Al-15% Mg$_2$Si composite revealed a brittle mode of failure in cast composite, however modification by La increased fine dimples and reduced the number of decohered particles.

References


