Effect of Heat-Treatment on Microstructure and Mechanical Properties of Sonicated Multicomponent AlMgSiCuZn Alloy

Kwangjun Euh, Jae-Gil Jung, Eun-ji Baek, Jung-Moo Lee, and Hyoung-Wook Kim

Abstract

In this study, an $AlMg_8Si_9Cu_{10}Zn_{10}$ (in wt%) alloy is fabricated with a high volume fraction of coarse secondary phases, which is higher fraction than in the conventional piston alloys. Ingots are cast in a permanent mold after an ultrasonic melt treatment for 60 s at the temperature range of 750–700 °C. Microstructure of AlMgSiCuZn alloy consists of Si, Zn, Mg_2Si, Q-$Al_5Cu_2Mg_8Si_6$, and θ-Al_2Cu phases. By the heat-treatment at 440 °C, Q-phase at the vicinity of blocky Mg_2Si phase grows and the roundness of the second phases increases with respect to the heat-treating time. Compared with the as-cast specimen, room-temperature ultimate compressive strength of the heat-treated specimens increases. However, maximum compressive stress at 350 °C is slightly decreased by heat treatment. The formation of fine clusters increases the ultimate compressive strength, while the spheroidization of bulky secondary phases during heat treatment deteriorates the ultimate compressive strengths.

Keywords

Heat-treatment • Microstructure • Ultrasonic melt treatment • Multi-component • AlMgSiCuZn alloy

Introduction

Recently, much research has been put forth on the high entropy alloys (HEAs) due to their extraordinary high strength and thermal stability at elevated temperatures [1, 2]. Studies on low-density multicomponent alloys have been already started and Yang et al. reported that $Al_{80}Li_5Mg_5Zn_5Cu_5$ (at.%) alloy consisted of Al solid-solution and intermetallic compounds (IMCs) exhibiting excellent room-temperature compressive strength despite of the low ΔS_{conf} value (0.78R). [3]. Coarse IMCs act as main sites of stress concentration and thus deteriorate the mechanical properties [4–6]. Hence, the IMCs needs to be refined for further improving the mechanical properties of low-density multicomponent alloys. Ultrasonic melt treatment (UST) is known to reduce the casting defects [7] with refining the microstructure [5]. The solution treatment can also affect mechanical properties of low-density multicomponent alloys, since it changes constituent phases and modifies the morphology of IMCs [8, 9].

In the present study, the effect of heat treatment on the microstructure and mechanical properties of sonicated multicomponent $Al_{70}Mg_{10}Si_{10}Cu_5Zn_5$ alloy were analyzed. Furthermore, the mechanical properties of $Al_{70}Mg_{10}Si_{10}Cu_5Zn_5$ alloy were compared to those of commercial Al alloys for piston applications.

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Experimental

A 1.5 kg of $Al_{70}Mg_{10}Si_{10}Cu_5Zn_5$ alloy melt was produced at 800 °C in an induction melting furnace using high-purity (99.9 wt%) metals (Al, Mg, Zn) and master alloys (Al-25Si, Al-30Cu). The melt was sonicated for 60 s at the

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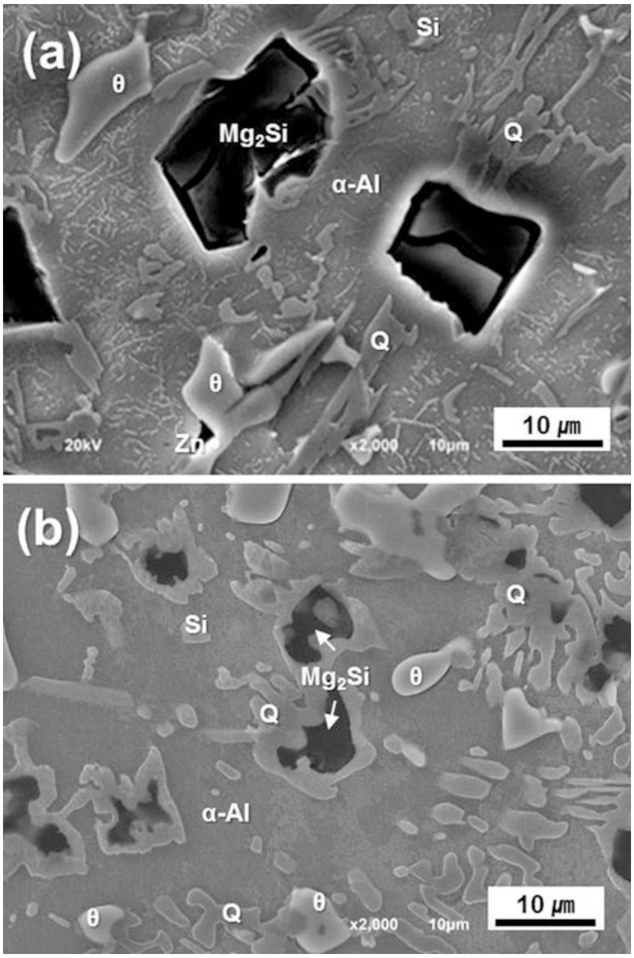

Fig. 1 SEM micrographs of **a** as-cast alloy and **b** heat-treated alloy for 10 h

temperature range of 750–700 °C using a Ti sonotrode [10], and followed by casting in a permanent mold at 700 °C. The sonicated $Al_{70}Mg_{10}Si_{10}Cu_5Zn_5$ alloy was heat-treated at 440 °C for various holding times (1–10 h).

Microstructures were observed using an optical microscope and a scanning electron microscope equipped with an energy dispersive X-ray spectroscope. The grain structure was examined using an electron backscatter diffraction (EBSD) instrument installed in a field emission scanning electron microscope. The precipitates were examined using a field emission transmission electron microscope. Cylindrical samples (Ø8 × 12 mm) were prepared for compression tests. The compression tests were performed at 25 °C using an Instron 5982 universal testing machine with a strain rate of 5×10^{-4} s^{-1}. Compression tests were also conducted at elevated temperatures ranging from 100 to 350 °C up to strain of 0.5 using a Thermecmastor-Z testing machine with a strain rate of 5×10^{-3} s^{-1}.

Results and Discussions

Several secondary phases are observed in the as-cast alloy (Fig. 1a) and are identified as Mg_2Si, Q, Si, θ and Zn by analyzing their chemical compositions. Q phases are observed adjacent to Mg_2Si particles and Zn phases are observed near θ particles. This is probably related to the serial formation of secondary phases; Q and Zn phases are formed after Mg_2Si and θ phases, respectively. By the heat treatment, both area fraction and size of primary Mg_2Si particles are decreased, while area fraction of Q phase increases (Fig. 1b). The secondary phases are spheroidized during the heat treatment.

Table 1 shows the size and area fraction of secondary phases in $Al_{70}Mg_{10}Si_{10}Cu_5Zn_5$ alloy with respect to the heat treatment time at 440 °C. The area fraction of Mg_2Si phase deceases gradually from 10.3 to 6.0% with increasing heat treatment time. At the same time, the area fraction of Q increases from 11.5 to 14.3%. This is due to the transformation from unstable Mg_2Si phase to stable Q during heat treatment. The area fractions of θ and Si phases in the as-cast alloy are 7.1 and 3.3%, and these values are not much changed during the heat treatment. During the heat treatment, the total area fraction of secondary phases remains to

Table 1 Size and area fraction of secondary phases in $Al_{70}Mg_{10}Si_{10}Cu_5Zn_5$ alloy

Phase		Heat treatment time (h)			
		0	1	4	10
Size (μm)	Mg_2Si	20.6	18.4	14.5	14.2
	θ-Al_2Cu	11.5	10.5	9.7	9.8
	Q-Al_5Cu,Mg_sSi_6	6.7	6.4	5.7	5.6
	Si	4.2	3.8	3.5	3.6
Fraction (%)	Mg_2Si	10.3	8.9	7.3	6.0
	θ-Al_2Cu	7.1	7.0	6.3	6.7
	Q-Al_5Cu,Mg_sSi_6	11.5	11.2	12.3	14.3
	Si	3.3	3.9	4.5	4.4
	Total	32.2	31.0	30.4	31.4

similar values (30.4–32.2%). The size of Mg_2Si phase decreases from 20.6 to 14.2 µm due to the dissolution of Mg_2Si during the heat treatment, while the sizes of Q, Si and θ phases are not much changed.

Needle-like precipitates are observed in the Al matrix of as-cast alloy (Fig. 1a), which are found to be Q and θ′ phases through the EDXS analysis (Fig. 2). Their size is in a wide range of 10–1000 nm. However, the needle-like Q and θ′ phases are not observed in the heat-treated alloys and very fine precipitates less than 10 nm are present.

Thermal analysis via differential scanning calorimetry reveals that the as-cast alloy contains both ellipsoidal GP zones and θ′ phase (Fig. 3). On the other hand, the heat-treated alloy contains both spherical and ellipsoidal GP zones (Zn clusters). The heat treatment also causes the dissolution of θ′ and θ phases into the Al matrix and then probably Cu clusters can form at room temperature. The DSC measurements confirm that the fine precipitates observed in the heat-treated alloy are spherical and ellipsoidal GP zones as well as Cu clusters (GP zones). Such a

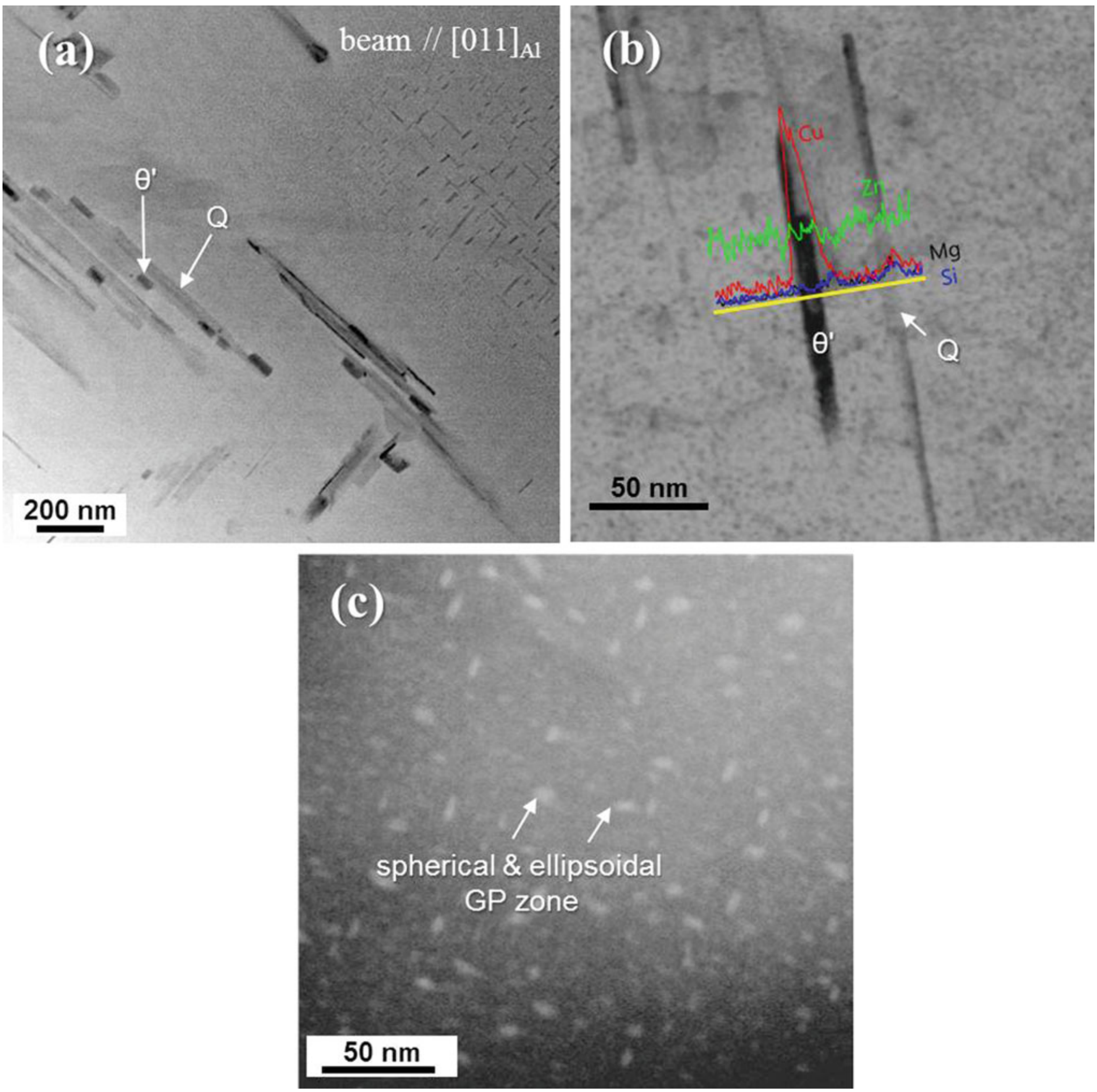

Fig. 2 TEM micrographs of **a**, **b** as-cast alloy and **c** heat-treated alloy for 4 h [11]

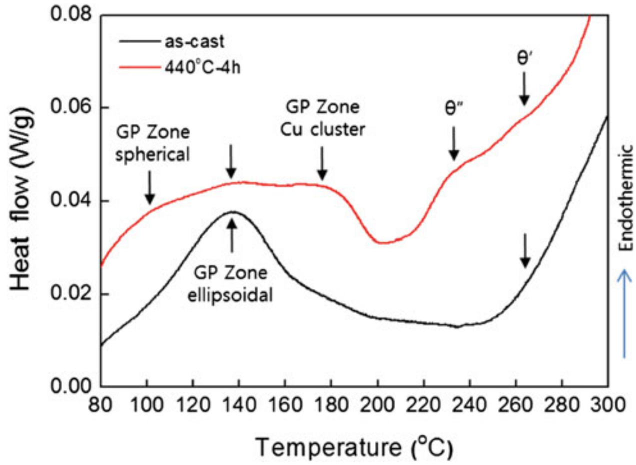

Fig. 3 DSC curves of as-cast alloy and solution-treated alloy at 440 °C for 4 h [11]

Table 2 Compressive strength at room temperature and 350 °C

Temperature	Compressive strength	Heat treatment time (h)			
		0	1	4	10
RT	$\sigma_{0.2}$	414	417	417	406
	σ_{max}	681	744	742	723
350 °C	σ_{max}	121	119	118	113

formation of Zn and Cu clusters during holding at room temperature (i.e. natural aging) results from the high Zn (∼15 wt%) and Cu (∼3 wt%) concentrations of the Al matrix in the heat-treated alloy enough for them to precipitate even at room temperature [12–14].

The compressive yield strengths ($\sigma_{0.2}$) of heat-treated alloys for 1, 4 and 10 h are 417, 417 and 406 MPa, respectively. It is thought that the yield strength was not significantly affected by heat treatment, considering as-cast alloy (414 MPa). The σ_{max} value shows a maximum of 744 MPa at the heat treatment time of 1 h, which is attributed to the enhanced solid-solution hardening by Zn and Cu atoms and/or clustering hardening by GP zones. With further heat treatment time, the σ_{max} value was gradually decreased to 742 MPa at 4 h and 723 MPa at 10 h.

At the elevated temperature of 350 °C, the σ_{max} value decreases gradually from 121 to 113 MPa with increasing heat treatment time. Particularly at high temperatures when the Al matrix are getting softer, the interconnected network structure of rigid phases plays a crucial role in mechanical properties by transporting external load from soft Al matrix to rigid secondary phases [8, 9]. Therefore, the decreased σ_{max} value at 350 °C with increasing heat treatment time is most likely due to the partial break-up of network structures of rigid phases caused by their spheroidization (Table 2).

Conclusions

In this study, the multicomponent $Al_{70}Mg_{10}Si_{10}Cu_5Zn_5$ alloy was successfully fabricated by commercial Al casting procedure combined with ultrasonic melt treatment. The effects of heat treatment on the microstructure and mechanical properties at room and elevated temperatures were examined. The formation fine clusters such as spherical or ellipsoidal GP zones increased the ultimate compressive strength at room temperature. During the heat treatment, the phase transformation from Mg_2Si to Q phase gradually occurred along with the spheroidization of secondary phases. The spheroidization of secondary phases occurring during heat treatment deteriorated the ultimate compressive strengths.

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