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Effect of transition elements on the microstructure and tensile properties of Al–12Si alloy cast under ultrasonic melt treatment

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ABSTRACT

This paper shows that the addition of transition elements significantly influences the microstructure and tensile properties of Al–12Si alloy cast under ultrasonic melt treatment (UST). The alloys contained primary Si, eutectic Si and a variety of intermetallic compounds (IMCs); the addition of Mn and Ni changed the solidification sequence by forming primary α-$Al_{15}(Fe,Mn)_4Si_2$ and ε-Al_3Ni prior to primary Si formation. The primary Si and primary IMCs competitively consumed the nucleation sites introduced by UST, thereby influencing their refining efficiencies; the efficiency of primary Si refinement by UST increased with increasing the fraction of primary Si formed prior to IMC formation, whereas it deteriorated with increasing primary IMC fraction. The refining efficiency of eutectic Si and eutectic IMCs was not affected by the type and fraction of the primary phase. Using a Ti sonotrode for UST caused Ti contamination, resulting in grain refinement by forming $Ti(Al,Si)_3$ particles and increasing the amount of Ti solutes. Regardless of transition elements content, the application of UST improved the tensile strength at 25 °C and 350 °C. The refinement of IMCs caused by UST allowed the alloy to contain more IMCs without deterioration of room-temperature tensile strength. This enhanced the increment of high-temperature tensile strength by IMCs. Ductility of heavily alloyed systems was also improved by UST.

1. Introduction

Multicomponent Al–Si alloys have been widely used in piston production due to their high strength, low coefficient of thermal expansion and excellent castability [1–3]. In addition to Si, these piston alloys generally contain transition elements (e.g., Cu, Ni, Fe, Mn) that form thermally stable intermetallic compounds (IMCs), which make it possible to attain the required mechanical properties [1–3]. With increasing demands for greater fuel efficiency, there is a need to develop high-strength piston alloys that are able to withstand severe operating conditions. To this end, many researchers are currently engaged in optimizing their chemical compositions [4–10] and process variables such as the casting mold material [11] and heat treatment [12].

Ultrasonic melt treatment (UST) has been applied to Al–Si piston alloys because it effectively refines the microstructure, thereby improving the mechanical properties [13,14]. The application of UST expands the upper limit of the transition element content that can be used in the alloy by refining the coarse Si and IMCs that form in highly alloyed systems, further improving the mechanical properties of Al–Si piston alloys [13]. Additional studies have investigated the combined effects of UST and alloying elements for developing high strength Al–Si piston alloys [15–17].

Recently, the present authors [15] examined the combined effects of UST and Si addition on the microstructure and tensile properties of Al–(12,15,18)Si–4Cu–3Ni–1Mg–0.5Fe (wt%) alloys and found a pronounced improvement in the tensile properties at room and elevated temperatures. Sha et al. [16] reported a similar result: the UST-induced improvement in high-temperature tensile strength increased from 23 to 32 MPa with increasing Co content from 0 to 1.05 wt% in the hypereutectic Al–20Si–2Cu–1Ni–0.6Mg–0.7Fe (wt%) system. Lin et al. [17] also showed that the improvement in high-temperature tensile strength with UST increased with increasing concentration of Mn or Fe using a hypereutectic Al–17Si–2Cu–1Ni–0.4Mg (wt%) alloy.

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The additions of transition elements change the type and formation sequence of secondary phases, thereby influencing the refining behavior of each phase under UST. However, the effect of transition elements on the solidification microstructure and tensile properties of Al–Si alloy cast under UST has not been fully understood yet.

Therefore, the present study systematically investigates the effects of UST and transition elements (Cu, Ni, Fe and Mn) on the microstructure and mechanical properties of Al–12Si (wt%) piston alloy. The primary phases, eutectic phases, and grains were quantitatively evaluated for distribution, size, and area fraction in alloy microstructures processed with UST. The microstructures were analyzed in relation to the tensile properties at room and elevated temperatures. Based on the findings in this study, we suggest that the refinement of primary phases (Si, IMCs) is dependent on their competitive nucleation under ultrasonic irradiations.

2. Experimental procedure

2.1. Materials

Ingots of five Al–12Si piston alloys were provided by Dong Yang Piston Co. (Ansan, Republic of Korea), and their chemical compositions were measured by ARL3460 optical emission spectroscopy and iCAP6500 inductively coupled plasma-optical emission spectroscopy (see Table 1). Note that in addition to different concentrations of transition elements (Cu, Ni, Fe, and Mn), the ingots all contain phosphorus (20–34 ppm), which is necessary to refine primary Si because AlP inclusions act as heterogeneous nucleation sites [18–21]. To examine the role of AlP in refinement of the primary Si particles, Al–25Si binary alloy with and without 0.05 wt% P was also prepared.

2.2. Casting and heat treatment

Al–12Si piston alloys and Al–25Si binary alloy were remelted at 750 °C and 850 °C in an electric resistance furnace, and then degassed by Ar gas bubbling filtration (GBF) during 20 min. The degassed melts, each weighing approximately 1 kg, were then poured into a copper book mold (245 mm × 70 mm × 200 mm) that had been preheated to 200 °C. Considering the formation temperatures of primary Si, the melt pouring temperatures of Al–12Si and Al–25Si alloys were determined as 700 °C and 800 °C, respectively. The cooling rate of solidifying melts from 650 °C to the eutectic arrest temperature (~560 °C) was ~7.5 °C/s [15].

A titanium sonotrode preheated to 200 °C was injected into each 1 kg melt to introduce ultrasonic waves with an amplitude and frequency of 20 μm and 19 kHz, respectively. The UST was performed for 1 min within a temperature range of 750 to 700 °C for Al–12Si piston alloys and a temperature range of 850 to 800 °C for Al–25Si binary alloy, after which the melts were poured into the same mold. The details about the ultrasonic process can be found in a previous article [15]. The ingots were solution-treated at 490 °C for 2 h, and then aged at 230 °C for 5 h (i.e., T7 heat treatment).

2.3. Microstructural observations

Samples for microstructural observation were taken from each ingot at a position one half of its length and width, and one quarter of its height. The microstructure was observed using an optical microscope (OM, Nikon, MA200) and a scanning electron microscope (SEM, JEOL, JSM-6610LV) equipped with energy diverse X-ray spectroscopy (EDXS, JEOL, INCA Energy). An image analyzer (IMT, i-Solution) was used to quantitatively measure the size (maximum length) and area fraction of the secondary phases. Three OM images (200× magnification) were used for analyzing primary Si particles, while ten OM images (1000× magnification) were used for analyzing eutectic Si and IMC particles. The grain structure was examined using an electron backscatter diffraction (EBSD) instrument installed in the SEM (TESCAN, CZ/MIRA I LMH) with a step size of 10 μm. The fcc-Al grains with sizes greater than 50 μm were averaged to separate them from primary Si particles having a diamond cubic structure.

The precipitates were observed through a transmission electron microscope (TEM, JEOL, JEM 2100F). The cross-sectional TEM samples were fabricated by using a focused ion beam and they were placed on Mo grids. To estimate the amount of precipitates formed during T7 heat treatment, the electrical resistivity of as-cast and T7 treated alloys was measured at 25 ± 1 °C using a sourcemeter (Keithley, Model 6220) and a voltmeter (Keithley, Model 2182), as outlined in ASTM F76–08 [22].

2.4. Tensile tests

Room-temperature tensile tests of T7 treated alloys were performed using an Instron 4206 universal testing machine with a crosshead speed of 1.5 mm/min, as outlined in ASTM E8/E8M–13a [23]. Tensile tests were also performed at 350 °C in accordance with ASTM E21–09 [24] after isothermally maintaining each sample at 350 °C for 100 h to simulate the piston operating condition. The crosshead speeds during high-temperature tensile tests were 0.125 and 1.5 mm/min before and after the yield point. Dogbone-shaped (gage section: Ø6 × 25 mm) samples were used for tensile tests.

3. Results

3.1. Thermodynamic calculation

Fig. 1 shows the plot of temperature versus solid mole fraction (f_s) during Scheil-Gulliver solidification of Alloy 1, which was calculated using Thermo-Calc software [25] with the TCAL3 database. A minor alloying element, Ti, was excluded in the calculation. Primary Si and $\varepsilon\text{-Al}_3\text{Ni}$ phases start to form at 577.3 °C and 568.9 °C, respectively. Then, complex reactions take place at temperatures ranging from 560.0 to 509.8 °C, resulting in the formation of eutectic Si, various IMCs (e.g., $\varepsilon\text{-Al}_3\text{Ni}$, $\delta\text{-Al}_3\text{CuNi}$, $\gamma\text{-Al}_7\text{Cu}_4\text{Ni}$, $\text{Q-Al}_5\text{Cu}_2\text{Mg}_8\text{Si}_6$, $\theta\text{-Al}_2\text{Cu}$, $\text{M-Mg}_2\text{Si}$, etc.) and an fcc-Al matrix. From the thermodynamic calculations, it is expected that various IMCs

Table 1
Chemical composition of Al–12Si piston alloys and their mole fraction of intermetallic compounds.

Alloy	Chemical composition (wt.%)										Mole fraction of intermetallic compound (%)	
	Al	Si	Cu	Ni	Mg	Fe	Mn	Ti	P	Transition element	Non-equilibrium solidification	Equilibrium at 350 °C
1	Bal.	12.08	3.24	2.36	0.81	0.24	0.20	0.08	0.0021	6.12	6.23	10.45
2	Bal.	11.90	3.22	2.34	0.97	0.41	0.39	0.09	0.0020	6.45	8.44	11.91
3	Bal.	12.15	3.32	2.51	0.82	0.24	0.59	0.08	0.0022	6.74	9.08	12.00
4	Bal.	12.81	4.17	2.26	0.86	0.43	0.35	0.09	0.0034	7.30	8.07	12.41
5	Bal.	11.97	3.79	3.39	0.82	0.50	0.18	0.10	0.0023	7.96	11.80	13.92