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Improved mechanical properties of near-eutectic Al-Si piston alloy through ultrasonic melt treatment

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ABSTRACT

The effects of ultrasonic melt treatment (UST) on the microstructure and mechanical properties of Al-12.2Si-3.3Cu-2.4Ni-0.8Mg-0.1Fe (wt%) piston alloy were systematically investigated. Rigid colonies consisting of primary Si, eutectic Si, Mg_2Si and various aluminides (ε-Al_3Ni, δ-Al_3CuNi, π-$Al_8FeMg_3Si_6$, γ-Al_7Cu_4Ni, Q-$Al_5Cu_2Mg_8Si_6$ and θ-Al_2Cu) were observed in the as-cast alloys. The sizes of the secondary phases, eutectic cell and grain were significantly decreased by UST because of the enhanced nucleation of each phase under ultrasonic irradiation. The yield strength, tensile strength and elongation at 25 °C were significantly improved by UST mainly because of the refinement of the microstructures. Both tensile strength and elongation at 350 °C were also improved by UST despite the unchanged yield strength.

1. Introduction

Al-Si alloys have been widely used in high-temperature applications such as in fabricating automobile engine pistons, because of their high strength and excellent resistance to abrasion and fatigue at ambient and elevated temperatures [1]. With increasing demands of high fuel efficiency, lighter pistons that can withstand higher temperatures are required. Thus, many investigators have made extensive efforts to improve the mechanical properties of Al-Si piston alloys.

Transition elements such as Mn [2], Fe [3], Ni [4], Cu [4,5], Cr [6], Co [7] and Zr [8] have been added to improve the mechanical properties of Al-Si piston alloys because these elements form rigid phases that are thermally stable at elevated temperatures [9]. Hence, recent Al-Si piston alloys contain Si (11–23 wt%), Cu (0.5–5.5 wt%), Mg (0.6–1.3 wt%), Ni (0.5–3.0 wt%), Fe (< 1.3 wt%), Mn (< 1.0 wt%) and other elements (Co, Zr, Ti, V, etc.) [10]. The optimization of processing variables such as cooling rate and heat treatment have been also used to improve the mechanical properties of Al-Si piston alloys [11].

Ultrasonic melt treatment (UST) has been applied to improve the mechanical properties of Al alloys because the UST effectively reduces the porosity and refines the microstructures [12–16]. The refining effect of UST has been explained by the hypothesis that the dendritic grains can be broken and distributed by ultrasonic vibrations, acting as heterogeneous nucleation sites for α-Al and/or secondary phases [12,13]. It has also been suggested that the decreased undercooling required for nucleation during the expansion and collapse of cavitation bubbles that are introduced by ultrasonic vibrations is responsible for the refinement of microstructure [14–16].

Beneficial effects of UST are highly expected in the case of Al-Si piston alloys containing a high volume fraction (~20%) of coarse secondary phases. Sha et al. [17] and Lin et al. [18] reported that at room temperature and elevated temperature (350 °C), UST improved both strength and ductility of hypereutectic Al-Si piston alloys such as Al-20Si-2Cu-1Ni-0.6Mg-0.7Fe-(0–1.1)Co and Al-17Si-2Cu-1Ni-0.4Mg-(0.2–2.0)Fe-(0.4–0.8)Mn; this improvement was attributed to the refinement of pre-eutectic phases such as primary Si and Fe-bearing intermetallic compounds. However, until now, few studies have focused on the effects of UST in near-eutectic Al-Si piston alloys whose microstructure and mechanical properties are dominated by eutectic phases.

Therefore, in this study, UST was applied to near-eutectic Al-12.2Si-3.3Cu-2.4Ni-0.8Mg-0.1Fe (wt%) piston alloy and then microstructural changes (pre-eutectic phases, eutectic phases, grain, etc.) due to UST were quantitatively measured through two-dimensional (2-D) and three-dimensional (3-D) observations. The effects of UST on tensile properties and fracture mechanisms at ambient and elevated temperatures were also investigated.

2. Experimental procedure

The specimens used in the study were provided by Dong Yang

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Table 1
Chemical composition of Al-Si piston alloys with and without UST (wt%).

Alloy	Si	Cu	Ni	Mg	Fe	Mn	Ti	P	Al
w/o UST	12.18	3.28	2.42	0.83	0.14	0.02	0.11	0.0019	Bal.
w/ UST	11.75	3.16	2.22	0.76	0.12	0.01	0.12	0.0017	Bal.

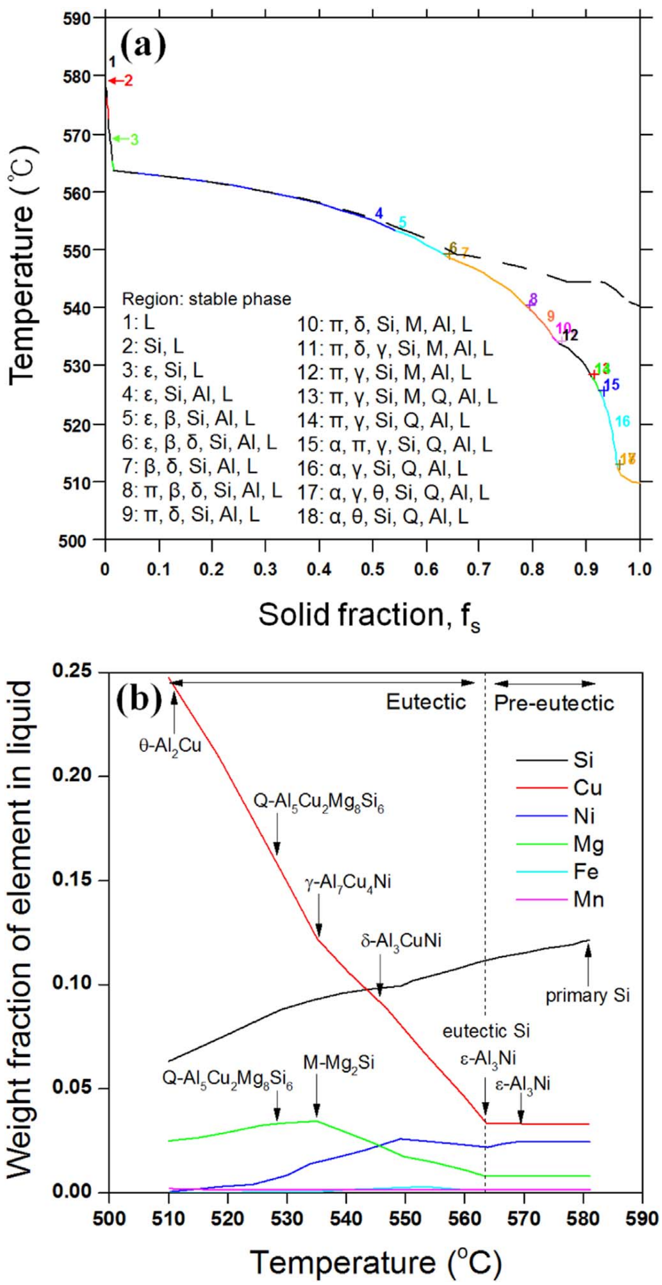

Fig. 1. (a) Temperature-solid fraction curve and (b) chemical composition of liquid phase during Scheil-Gulliver solidification of Al-Si piston alloy.

Piston Co. (Ansan, Republic of Korea). One kilogram of near-eutectic Al-Si piston alloy was re-melted at 750 °C in an electric resistance furnace and degassed using Ar gas bubbling filtration (GBF). The degassed melts were poured at 700 °C into a permanent copper mold (245 mm × 200 mm × 70 mm^3), which was preheated to 200 °C (hereafter referred to as without UST).

The UST was performed for 60s over the temperature range of 750–700 °C using a titanium horn connected with a high speed bipolar amplifier (NF corporation, HSA4052) and a multifunction synthesizer (NF corporation, WF1945B). The amplitude and frequency of ultrasounds were approximately 20 μm and 19 kHz, respectively. The titanium horn was preheated to 200 °C to reduce the chill effect of cold horn and then it was immersed to 20 mm below the top melt surface. The ultrasonic-treated melts were poured into the same mold (hereafter referred to as with UST). The chemical compositions of as-cast alloys with and without UST were measured three times per each sample using an optical emission spectroscopy (OES, Thermo Scientific, ARL 3460) and their averaged values were listed in Table 1. To examine the solidification events, the cooling curves of the solidifying alloys were recorded using a K-type thermocouple more than two times to ensure reproducibility.

After the specimens were mechanically polished, the microstructures were observed using an optical microscope (OM, Nikon, MA200) and a scanning electron microscope (SEM, JEOL, JSM-6610LV) equipped with an energy dispersive X-ray spectroscope (EDXS, JEOL, INCA Energy). The grain structure was examined using an electron backscatter diffraction (EBSD) instrument installed in a field emission scanning electron microscope (FE-SEM, TESCAN, CZ/MIRA I LMH). An image analyzer (IMT, i-Solution) was used to quantitatively measure the size, roundness and volume fraction of the secondary phases from ten OM images taken at x1000 magnification. 3-D images of the secondary phases were obtained using an automatic serial sectioning machine (UES Inc., Robo-Met. 3D) and 3-D analysis software (FEI, Avizo Fire 7). X-ray diffraction was performed to characterize the secondary phases using Cu-Kα radiation. The density of each alloy was measured using an analytical balance (Mettler Toledo, AG285).

Room-temperature tensile test was performed using an Instron 4206 testing machine with a crosshead speed of 1.5 mm/min. Tensile test was also performed at 350 °C with a crosshead speed of 0.125 mm/min according to ASTM E21 [19] after the samples were isothermally held for 100 h at the test temperature to simulate their operation conditions. Four dogbone-shaped (gage section: Ø6 mm × 25 mm^2) specimens per each alloy and each testing temperature were used to perform the tensile tests.

3. Results and discussion

3.1. Thermodynamic calculation

Fig. 1(a) shows the temperature vs. solid fraction (f_s) curve of the Al-Si piston alloy without UST during the Scheil-Gulliver solidification, which is calculated using the Thermo-Calc software [20] with the TCAL3 database. A minor element, Ti is excluded in calculation. The primary Si and ε-Al_3Ni phases were formed from liquid at 580 °C (region 2) and 569 °C (region 3), respectively. Then, various eutectic reactions take place at temperatures ranging from 564 to 510 °C. The Cu-free eutectic phase of ε-Al_3Ni was formed up to the medium stage of solidification (regions 4–6 in $f_s < 0.65$), followed by the formation of Cu-containing δ-Al_3CuNi eutectic phase (regions 6–11 in $0.65 < f_s < 0.85$). The eutectic phases with relatively higher Cu and Mg content such as γ-Al_7Cu_4Ni, Q-$Al_5Cu_2Mg_8Si_6$, θ-Al_2Cu and M-Mg_2Si form in the final stage of solidification (regions 10–18 in $f_s > 0.85$) after the Cu and Mg are sufficiently enriched in the remaining liquid (Fig. 1(b)).

3.2. Microstructures

Fig. 2(a) and (b) show the OM images of as-cast alloys without and with UST. Several secondary phases were observed and they were categorized into three groups. Dark gray phases were Si (blocky faceted primary Si_p and long platelet eutectic Si_e) and the black phases were Mg_2Si. The other phase of long bright platelets