

Effect of high power ultrasound on mechanical properties of Al-Si alloys

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Abstract. Effect of high power ultrasonic treatment on the solidification microstructures of Al-Si alloys containing varying content of solute Si (1, 2, 3 and 5 wt %) is investigated. Large variation in microstructures is seen and refinement of primary α -Al grains is observed. It is observed that increasing the weight percentage of solute along with ultrasonic treatment resulted in finer primary phase. By increasing the solute content from 1% to 5 wt.% in Al-Si alloys, hardness increased by about 38% without and 48% with ultrasonic treatment. Tensile strength of the alloys with ultrasonic treatment is higher as compared to those without ultrasonic treated.

1. Introduction

Al-Si alloys are major foundry alloys because of their good castability, remarkable wear and corrosion resistance, high specific strength and good weldability [1][2]. Al-Si alloys are employed for making engine blocks, automotive cylinder heads, pipefittings and aircraft structures [3]. Mechanical properties of Al alloys can be increased by decreasing the grain size of primary phase by solidification method [4]. Several methods are used for decreasing the grain size of light alloys i.e. rapid quenching, mechanical stirring, electromagnetic vibration and ultrasound solidification methods. In these methods, ultrasound solidification is promising method for grain refinement of alloys [5][6][7]. It is well documented that ultrasonic treatment (UST) of molten alloys changed the dendritic structure of the primary phase into equiaxed or non-dendritic structures [8][9][10]. In UST, immersing the ultrasonic probe into the molten metal produces acoustic waves that generate tensile stress in the melt, leading to formation of cavities in the melt [11][12]. In expansion cycle, these cavities grow in the molten metal and collapse during the compression cycles. The large amounts of energy released during collapsing of these cavities produces high temperatures (5000°C) and pressures of the order of 1000 atm [13][14]. As a result, cavitation, acoustic streaming, and mechanical effects are produced in the melt, which alter the diffusion and mass transfer characteristics of the melt [15]. During ultrasound-assisted solidification, two principle types of grain refinement mechanisms have been proposed, viz. cavitation enhanced heterogeneous nucleation and cavitation induced dendrite fragmentation. [1][11][13]. The former mechanism is further described with the assistance of the pressure pulse-melting point (T_m) mechanism, cavitation enhanced inclusion-wetting hypothesis, and cavitation induced endothermic vaporization theory. As per the pressure pulse-melting point mechanism, undercooling of the liquid phase occurs due to increase in pressure and consequently the melting point is increased, which is explained by the Clausius–Clapeyron equation (1) [16][17].

$$\frac{dT_m}{dP} = \frac{T_m(V_L - V_S)}{\Delta H} \dots \dots \dots (1)$$



Where T_m is the freezing point of the melt, P is the pressure, ΔH is the latent heat of freezing, and V_L and V_S are the specific volumes of liquid and solid phase. Cavitation enhanced nucleation mechanism is based on improving the wetting behavior of inclusions because of increase in pulse pressure in UST. The cavitation induced endothermic mechanism arises due to vaporization of liquid inside the expanded bubble. The cavitation induced dendrite fragmentation mechanism [13] is based on the shock waves produced by UST, which are expected to cause fragmentation of dendrites. In literature, there is no certain evidence as to which of the above ultrasonic mechanisms is dominant in grain refinement of Al alloys.

Both the UST and the solute content influence the microstructural and mechanical properties during solidification in Al alloys. However, systematic investigation the combined effect of amount of solute and UST in Al alloys is lacking in literature. In this work, the grain refinement in Al-Si alloys is studied by varying the Si content (1, 2, 3 and 5 wt. %) of the alloys and by employing UST. The resulting microstructure and mechanical properties of each Al alloy is investigated.

2. EXPERIMENTAL

Al-Si alloys of varying weight percentage of solute were prepared using master alloys. In all experiments, 300 g of charge (master alloy + pure Al) was melted in a graphite crucible (inside diameter: 60 mm). These alloys were melted at a temperature of $700^\circ\text{C} \pm 5^\circ\text{C}$, which is higher than the liquidus temperature. Before UST, the ultrasonic probe was preheated to 700°C . The graphite crucible was withdrawn from the electric resistance furnace at 700°C and ultrasonic probe was immersed in the molten metal until the melt solidified. At the time of UST, the power of the ultrasonic generator was 1.5kW. For microstructure examination, the cast samples in each condition were cut along the longitudinal section of each casting. Cast specimens were polished, and etched by Keller's reagent. Leica DMI 5000M microscope was used for optical microstructure examination. For grain size analysis, linear intercept (ASTM E 112-96) method was used. Each informed grain size data was averaged from measurements performed using at least five fields of view at $50\times$ magnification. Hardness tests of polished samples were performed on FIE-VM50 PC Vickers hardness tester using 1 kg load and a dwell time of 10 s. At least five hardness readings were measured. Tensile tests were performed according to ASTM B557 on Tinius Olsen H25 K-S machine using a constant crosshead speed of 0.1 mm/min corresponding to a strain rate of $10^{-3}/\text{s}$. Three samples were tested for each alloy. For the control specimen alloys that were not ultrasonically treated, "as-cast" term is employed.

3. RESULTS AND DISCUSSION

3.1. Characterization of phases

Figure 1 shows the XRD spectra of the Al-Si alloy samples. It shows that the phase constituents in all four Al-Si alloys are primary α -Al phase and secondary Si phase. Spectra d shows smaller 111 peak intensity of the secondary phase as compared to a, b and c spectra. The peak intensity of secondary phase increased with increasing solute content because of increase in amount of secondary phase.

3.2. Microstructural characterization:

Figure 2 shows the microstructures of as-cast and USTed Al-Si alloys. In the as-cast Al-1%Si alloy shown in Figure 2 (a), the coarse dendrites of the primary α -Al phase are present throughout the sample demonstrating normal dendrite growth mode with an average dendrite size of $1625\text{ }\mu\text{m}$. By increasing the solute content from 1 to 5%, the size of dendrite is decreased significantly for as-cast alloys. For as-cast Al-5%Si alloy, the primary dendritic grain size is about $768\text{ }\mu\text{m}$. Upon increasing the amount of solute, finer and globular grains are observed in UST alloys. For UST, lowest grain size is obtained in Al-5%Si alloy with an average grain size $124\text{ }\mu\text{m}$.

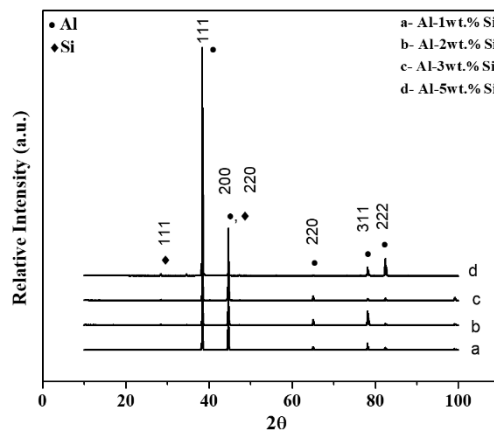


Figure 1: XRD analysis of Al-Si alloys

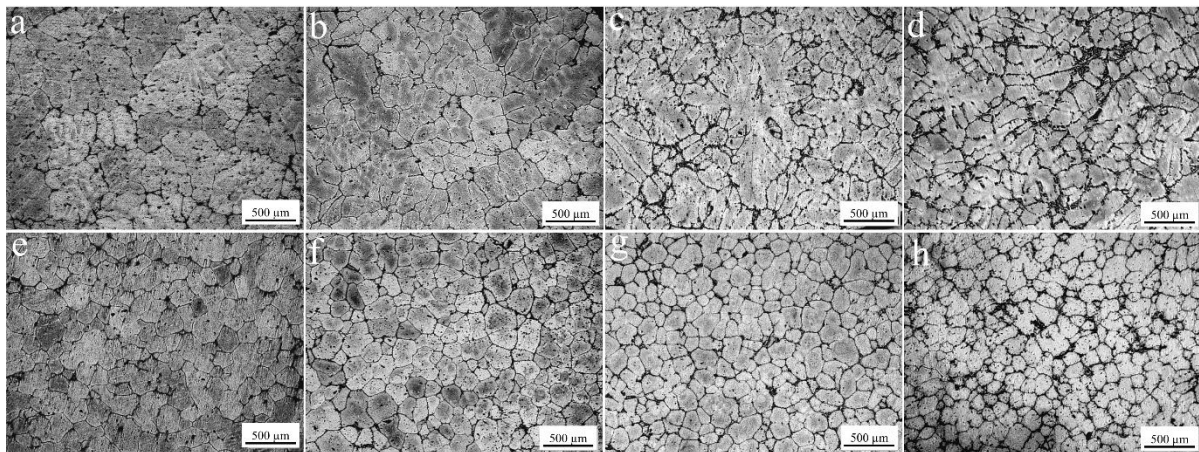


Figure 2. Optical micrographs of as-cast Al-Si alloys containing (a) 1%, (b) 2%, (c) 3%, and (d) 5% Si, and UST Al-Si alloys containing (e) 1%, (f) 2%, (g) 3%, and (h) 5% Si.

Increase in the solute content with the UST resulted in a decrease in grain size. In order to evaluate the relative effect of these parameters, the percentage decrease in grain size obtained from each variable is estimated (Table 1). For UST specimens, when the solute Si content is increased from 1 to 5 wt. %, i.e. by 5 times, the average grain size reduced by about 52%. Whereas, if we consider Al-1% Si (fixed solute content), when the UST was applied, the average grain size reduced by about 86 %, as compared to the as-cast alloy. For Al-5%Si alloy (fixed solute content) with UST, too, a similar amount of reduction in average grain size is obtained as compared to as-cast alloy. Thus, UST had much larger effect on the decrease in grain size as compared to the solute concentration.

3.3 Mechanical Properties of Al-Si alloy

Grain refinement resulting from both the solute and the UST can improve the mechanical behaviour of the processed alloys. The hardness values of the Al-Si alloys cast without and with UST for different solute contents are shown in Table 1. Increasing the amount of solute resulted in a noticeable increase in hardness for Al alloys without and with UST. The Hall-Petch equation relating hardness (H) and average grain size (d) of a polycrystalline material is: [18]

$$H = H_0 + K_H d^{-1/2} \dots \dots \dots (2)$$

where H_0 and K_H are the constants.

By increasing solute content in as-cast Al-Si alloys from 1 to 5 wt.%, the hardness increased by about 38%. It can be seen from Table 1 that the hardness of all the as-cast Al alloys is lower as compared to respective UST alloys. It is due to the coarse dendritic α -Al phase in as-cast alloys. UST increases the degree of refinement of α -Al phase and produces globular grains. As a result, the hardness is increased upon UST. The maximum value of hardness is obtained in Al-5Si alloy, which is 52 VHN with UST.

Figure 3 shows the engineering stress-strain curves of Al-Si alloys fabricated without and with UST. Variation in tensile properties is summarized in Table 1. It can be seen that the yield strength ($\sigma_{0.2}$), ultimate tensile strength (UTS) and ductility of all the UST Al-Si alloys are superior to as-cast alloys. Among all the Al-Si alloys, Al-5Si shows the maximum $\sigma_{0.2}$ and UTS values upon UST. It is due to higher amount of solute (Si content) and more refined and globular microstructure as shown in Figure 2 (h). It can be observed that that UTS, $\sigma_{0.2}$, and total elongation to fracture values are lowest for as-cast alloys. It is due to their higher porosity content. UST is known for its degassing ability, thus, it lowers the porosity [19][20]. Ultimate tensile strength (UTS) of the as-cast alloys shows abnormal behaviour. Upon doubling the solute content, UTS increased by about 13%. Further increase in the solute content to 3wt.% and 5wt.%, the UTS is decreased as compared to 2wt.% Si alloy. UTS of Al-1Si, Al-2Si, Al-3Si and Al-5Si UST alloys is about 41%, 45%, 56% and 79% higher than of as-cast alloys, respectively. Further, yield strength and % elongation values of the USTed Al-Si alloys are higher than those of as-cast alloys (Table.1). These results are related to the grain refinement observed after UST. The finer and globular the microstructure show the higher the value of the $\sigma_{0.2}$ and UTS. The resulting cavitation phenomenon from UST might have caused degassing of the molten metal and thus decreased porosity. Table 1 shows that total elongation of Al-Si alloy with UST is higher than as-cast alloys for respective solute contents.

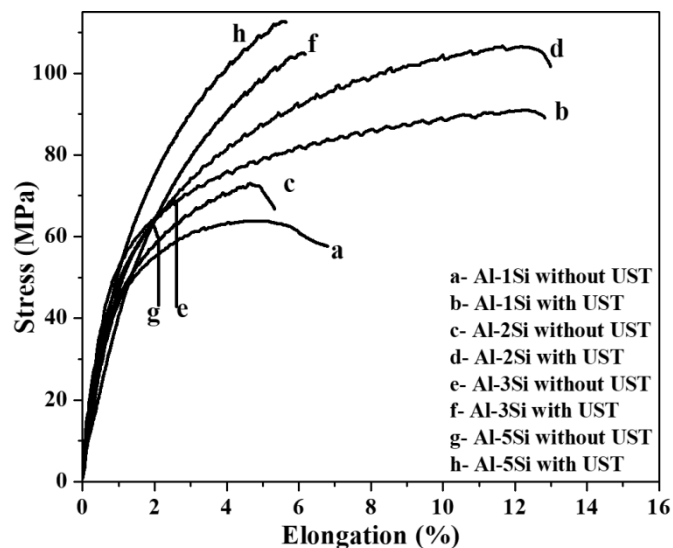


Figure 3. Engineering stress-strain curve of variously processed Al-Si alloys.

Table. 1 Average grain size and mechanical properties of Al-Si alloys without and with UST.

Material	Processing condition	Average grain size (μm)	Mechanical properties			
			Average hardness (VHN)	Tensile strength (MPa)	Yield stress (MPa)	Elongation (%)
Al-1%Si	As cast	1625	29.1	64	45	6.7
	UST	220	35.2	90	50	12.8
Al-2%Si	As cast	1300	32.4	72	46	4.7

	UST	190	40.5	104	51	12.5
Al-3%Si	As cast	1078	36	68	46	2.5
	UST	155	42	106	54	6.1
Al-5%Si	As cast	768	40.2	63	48	1.96
	UST	124	52	113	58	5.64

Conclusion

Influence of UST and solute content on the microstructure and mechanical properties of the Al-Si alloys is investigated. A number of interesting observations can be made from the experiment:

1. Nearly non-dendritic and fine grains are obtained in the solidified Al-Si alloys that are subjected to UST.
2. The average grain size gradually decreases with increasing solute content. Ultrasonic grain refinement of Al alloys results from the combined effects of both the solute and the ultrasonication of the melt and both effects are important.
3. The yield stress and UTS are highest for ultrasonically treated Al-5%Si alloy that contained largest amount of solute.
4. Total % elongation is higher for with UST alloys as compared to without UST alloys, at respective solute content.

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