Microstructure Evolution of A356 AlloyUnder Ultrasonic Vibration

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Abstract

Grain refinement and modification of eutectic silicon in Al-Si alloy are considered as important task resulting from solidification process. Two different approaches to grain refinement by solidification process have been pursued chemically stimulated and physically induced. The chemical route depends primarily on addition of grain refiner, while the physical relies mainly on the use of external field, such as ultrasonic vibration, which is the subject of this research work. Ultrasonic vibration was used to modify the microstructure of A356 alloy. The effect of ultrasonic vibration on the solidification of the A356 alloy was investigated and the obtained samples were characterized by optical microscopy, scanning electron microscopy (SEM) and mechanical properties as well. The results showed that both the primary aluminium and eutectic silicon were significantly refined; the dendritic primary aluminium became small polygonal and globular in some cases, in addition the plate-like or big spherical eutectic silicon turned into rod-like and small spheres during the solidification process under ultrasonic vibration. The mechanism of the microstructure evolution under ultrasonic vibration was also preliminarily discussed.

Keywords: Aluminium alloy A356, Al-Si, Ultrasonic vibration, Grain refinement, Modification of Si.

1. Introduction

Aluminium A356 alloy is one of the widely used casting aluminium alloys in aerospace and automobile industries because of its good mechanical strength, ductility, hardness, fatigue strength, pressure tightness, fluidity, and machinability. The A356 alloy contains about 50

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vol.% eutectic phases. The final microstructure is largely determined by the eutectic reaction. Due to its diamond cubic crystal structure which predominantly grows in {112} directions on (111) planes, silicon is a faceted phase with strongly anisotropic growth thus it is difficult to change the growth direction [1, 2]. In metallurgical scope, the research of ultrasonic vibration can be dated back to 1878 when Chernov proposed the original idea of improving cast metal quality by elastic oscillations [3]. Some recent investigations prove that high-intensity ultrasonic vibration has a significant effect on refining of both the primary aluminium phase and the eutectic silicon phase as well [4, 5]. So it is effective to change the morphology and size of Si phases in order to decrease the bad effect of Si phases on matrix and improve the mechanical property of Al–Si alloys [6].

Ultrasonic vibration is a new technique used for grain refining with some developing of this process has recently gained attention. The solidification structure and hence mechanical properties of the alloys, this process has now more attention [5-7]. The application of ultrasonic energy into molten alloys can bring about some nonlinear effects, such as cavitation, acoustic stream, emulsification, and radiation pressure, which can be used to refine microstructure, reduce segregation and degassing [5-7].

Some researchers [8], have reported the grain refinement mechanisms under ultrasonic vibrations. When the high intensity ultrasonic vibration is applied into the melt, the cavitations are induced ultrasonically, producing large instantaneous pressure and temperature fluctuations in the melt. These pressure and temperature fluctuations are likely to induce heterogeneous nucleation into the melt and to promote the dendrite fragmentation by enhancing solute diffusion through acoustic streaming. Among the methods mentioned above, heat treatment, chemical modification and application of magnetic field has already been widely used in industry for producing aluminium alloy with fine or fibrous eutectic silicon phase and refinement of α- aluminium phase. The outfield modification method has the advantages of being environmentally friendly, less cost, and easily to be combined with other technologies for treatment of liquid and solidified metal, so that it has a very good prospect in industry application.

In this paper, we focus on the effects of high-energy ultrasonic vibration on the microstructure properties of A356 alloy.

2. Experimental Procedure

2.1 Materials

The material of interest in this investigation is commercial aluminium – silicon based alloy, A356, with chemical composition as provided by the supplier "ASTM" shown in Table 1.

Table 1. Chemical composition of A356 "ASTM".

	Si	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**	**Ti**	**Other**	**Al**
Min	6.5	-	-	-	0.20	-	-	-	Balance
Max	7.5	0.6	0.25	0.35	0.45	0.35	0.25	0.15	

This alloy was supplied from Aluminium Company of Egypt in ingot form of A356-1, the delivered alloy A356, was chemically analysed (actual analysis) with the help of optical immesion process and the result is shown in Table 2.

Table 2. Chemical composition of A356.

Si	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**	**Ti**	**Other**	**Al**
7.36	0.15	0.0462	0.00129	0.329	0.00229	0.136	0.012	Balance

The aluminium – silicon phase diagram shows that the equilibrium eutectic constitution is about 12.6 wt% silicon. The chosen aluminium alloy in this study consider as in a hypoeutectic Al-Si alloy. Its liquidus temperatures is in the range of 610-660 °C. microstructure comprises both primary fcc aluminium solid solution containing 1.65-12.6 wt% silicon and eutectic containing silicon enriched aluminium and pure silicon [9].

2.2 Melt of Aluminium Alloys A356

1500 grams of A356 alloy were melt in a heat resistance furnace with using of a steel crucible coated from inside with graphite, and after the complete melting of the alloy, the temperature of the molten metal was kept for half an hour at a temperature of 740 °C± 10 °C, which a 100 °C higher than its liquidus temperature to allow the complete dissolution of the silicon particles. The thermocouple type K was used in measuring the temperature during melting process. The thermocouple was calibrated before and after each series of melts.

2.3 Pouring and Ultrasonic Application

The pouring of melton alloy A356 was carried out into a preheated permanent mould made of cast iron. The mould was held at the top of an ultrasonic sonotrode at temperatures "100 and 200 ºC", the dimension of the permanent mould were 40 mm inside diameter and 200 mm height. An ultrasonic generator unit with high power capacity was used, it consists of a 3.2 Kw electric power supply, and frequency of 22.4 kHz (acoustic generator), a water cooled converter, a booster, a probe, and an acoustic radiator made of titanium alloy Ti-6Al-4V. Figure 1 illustrates the setup of the experiment where ultrasonic vibration is applied directly to lower part of the mould through the sonotrode and the casting bar.

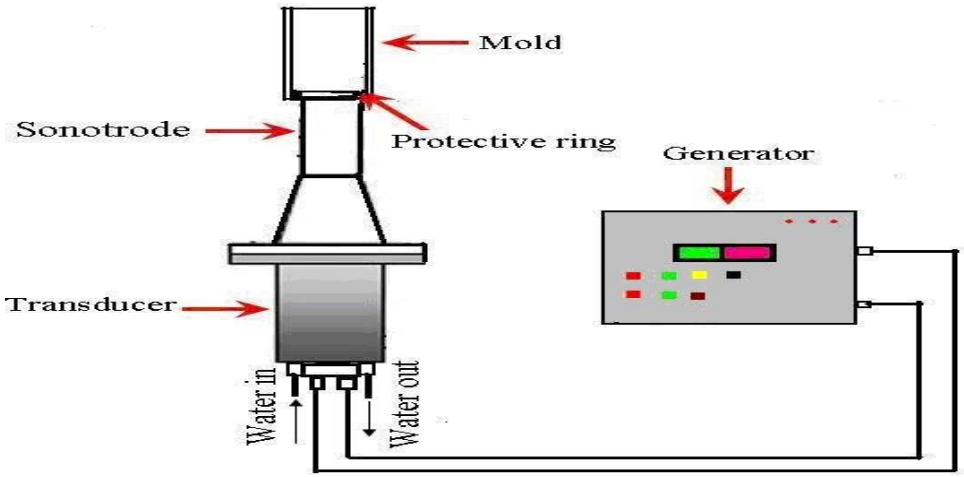

Figure 1. The setup experiment of ultrasonic treatment equipment.

2.4 Microstructure Analysis

Metallographic samples were cut from the same position for all experiments at distance 15, 30 and 95 mm from the bottom of the casting as shown in Fig. 2 and prepared according to used procedures development for aluminium alloys. Investigated specimens were obtained under different condition without and with ultrasonic vibration at constant power and different mould temperature of aluminium alloys A356.

Samples for microstructure analysis were taken from each cast sample by sectioning the cylinders perpendicular to its longitudinal axis, three specimens for microstructure analysis were made from one section, the location of specimens were at 5, 30, 95 mm respectively from the bottom of cast as shown in Fig. 2. The samples were first cut and ground using standard metallographic procedures. They were ground by using 240, 320, 400, and 600 grit papers. After grinding the samples were polished using 1 µm, and 0.05 µm Alumina suspension in water. Final polishing was done using silica suspension. Between each step, samples were thoroughly cleaned.

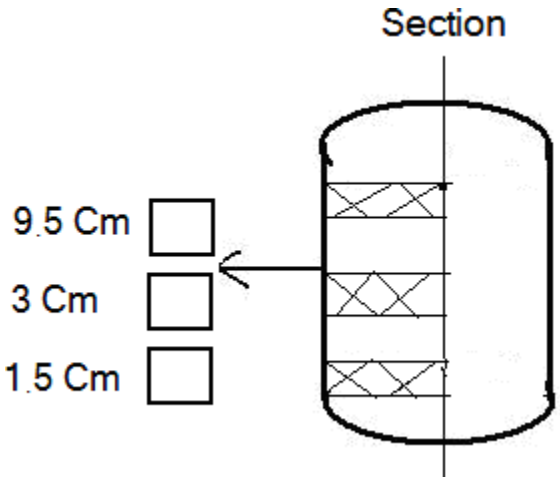

Figure 2. Location of specimens from bottom of cast cylinder of aluminium alloy A356.

2.5 Optical Microscopy and Quantitative Characterization

Samples used for characterization by optical microscopy were etched using 0.5% HF solution to reveal the resulting microstructure [2]. An optical microscope with quantitative

metallographic analysis capability was used to evaluate the shape and grain size of constituents. To evaluate α-Al grain size, length and width of eutectic silicon, each grain was delimited by a contour line using linear intercept method quantitatively analyzing software (image C).

2.6 Scanning Electron Microscope "S.E.M."

Scanning Electron Microscope "SEM" is used for the investigation of the three-dimensional α-aluminium phase, eutectic Si morphology and analysis of the composition of the intermetallic phases by deep-etched solution. Two deep etchants techniques were used in this research. First method, specimens were immersed in solution of 30% NaoH in distilled water at temperature of 70 °C for time from 3-20 minutes.[10]. Second, specimens were immersed in a solution of 15cm^{3}HCL, 10cm^{3}HF and 90cm^3 H_2O "distilled water" for time from 15-20 minutes, then the specimens were immersed in water from 1-2 minutes, then in alcohol from 3-5 minutes, finally the specimens were held in dryer at temperature 80 °C for time 60 minutes [11].

3. Results and Discussion

3.1 Microstructure of Aluminium Alloys A356 without Ultrasonic Vibration

Microstructures of the solidified samples taken from the preheated mould without ultrasonic vibration are presented in Figures 3and 4, the microstructure showed the overall matrix and eutectic Si morphology respectively. The microstructure of as-cast aluminium alloys A356 is a fully dendritic structure, the base metal Figure 4a exhibited coarse acicular eutectic silicon dispersed among the fully developed primary α-aluminium "light gray in the micrographs" dendrites and the eutectic silicon "dark gray in the micrographs" the length of the eutectic Si as shown in Table 3 is about 32.3μm and the average area of eutectic Si around 120 μm^2 was also present in the interdendritic areas. One branch of a primary α-aluminium was about 600 μm in length, as shown in Figure 3a, which indicated that the grain size was about a few micrometers as one grain usually contained several arms.

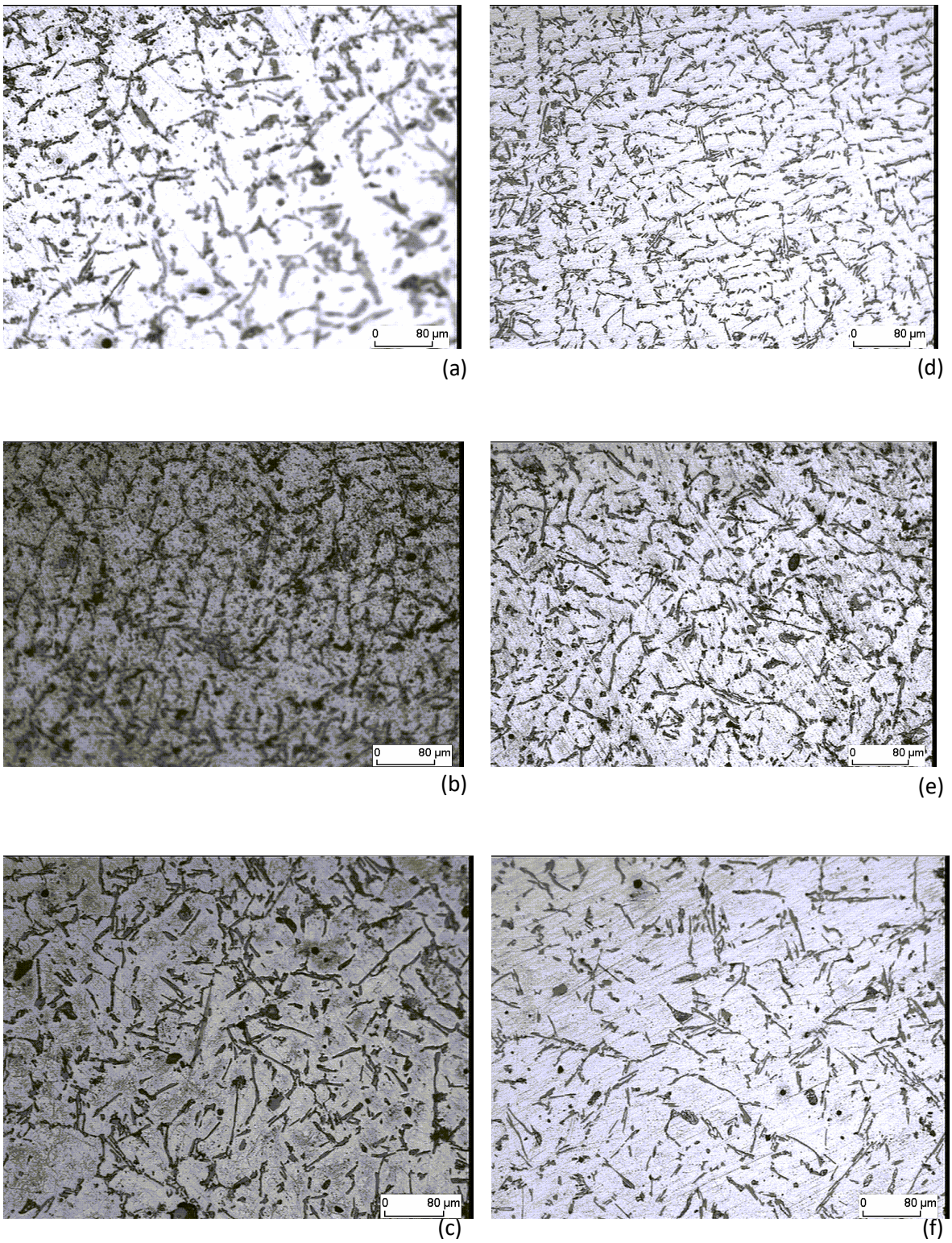

Figure 3. Comparison of the obtained microstructure without “a, b, c” and with the ultrasonic vibration “d, e, f” at mould temperature “100 °C”.

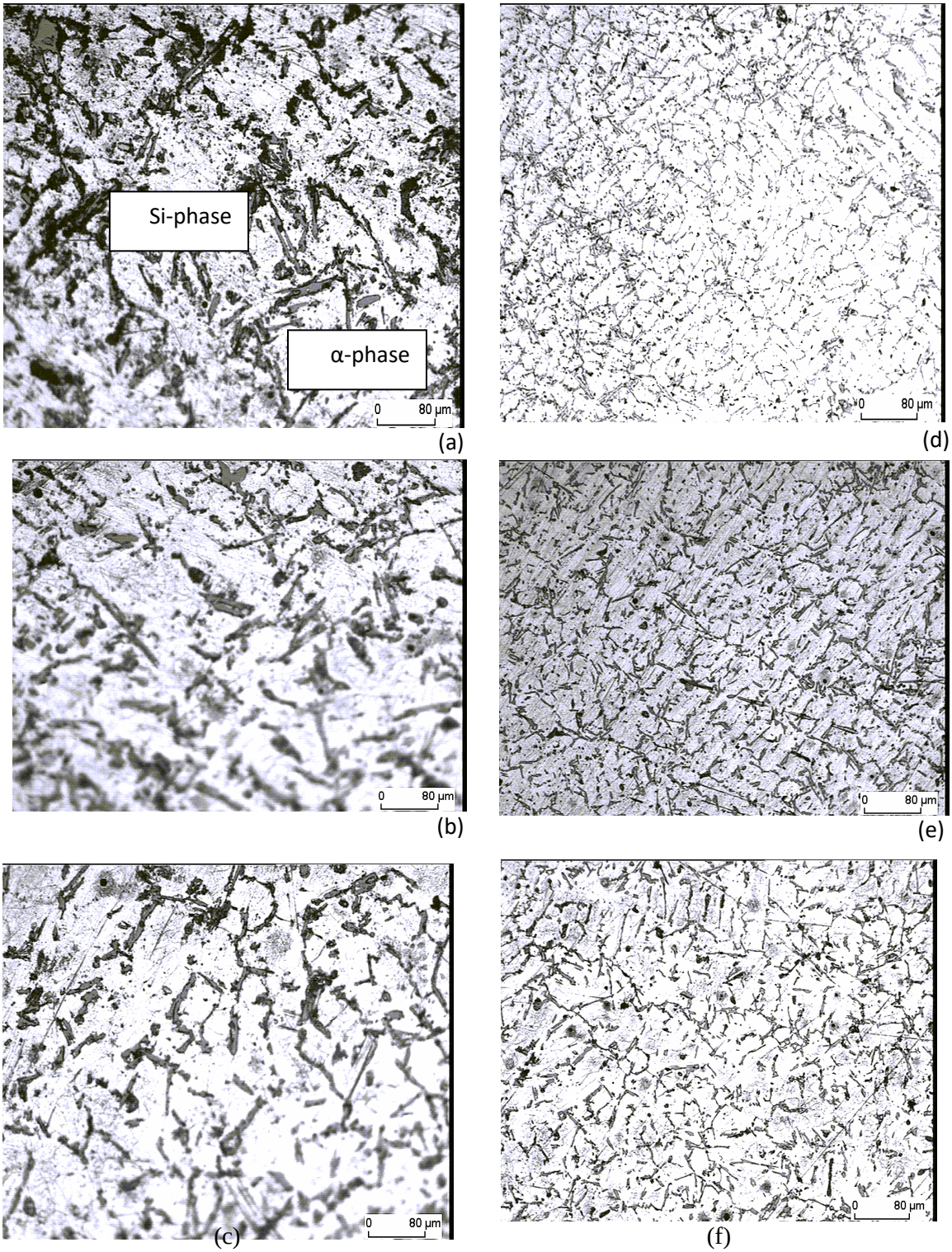

Figure 4. Comparison of the obtained microstructure without “a, b, c” and with the ultrasonic vibration “d, e, f” at mould temperature “200 °C”.

The microstructure of the hypoeutectic aluminium alloys (such as A356), usually consists of coarse dendritic α-Al solid solution and Al–Si eutectic, where Si usually assumes long plate or big spheres shape. Work of various researchers reported that the presence of intermetallic phases like the eutectic Al_2Cu "Chinese script" shaped α-Al_{15} $(Mn,Fe)_3Si_2$ and long and sharp needles of β-Al_5FeSi, which precipitate in the interdendritic and intergranular regions, and are strongly detrimental to the alloy mechanical and fatigue properties [12, 13].

Figures 3 and 4 show the comparison of the obtained microstructure without "a, b, c" and with "d, e, f" the ultrasonic vibration at different temperatures (°C) "100, 200" of preheated mould with ultrasonic power at 100% "power 3.2 Kw". Without ultrasonic vibration, the microstructure was dendritic and its average grain size was several micrometers. Upon the application of ultrasonic vibration at certain power, the dendritic arms were broken up and form a somewhat globular grain structure as shown in Figure 3.a&b. The average grain size was about 220 μm. This result is in accordance with previous work [5].

Without ultrasonic vibration, a coarse acicular plate-like form of eutectic silicon phases are observed in the aluminium matrix, linear intercept method quantitatively analyzed software (image C) were used to evaluate the length and width of eutectic silicon, the length of eutectic silicon as shown in table 3 is about 32.3 to 33.7 μm and width is about 4.1 to 4.4 μm, at mould temperature 100°C and 200°C, the morphologies of the silicon phases are of coarse particle-shape, and the α- Al phase tends to dendritic shape, the distributions are not uniform as clear shown in Figure 4. "a, b, c".

Table 3. Length and width of eutectic silicon

	Without ultrasonic vibration		With ultrasonic vibration	
	Length(μm)	Width(μm)	Length	Width
100°C	32.3	4.1	2.9	2.0
200°C	33.7	4.4	2.1	1.9

3.2 Microstructure of Aluminium Alloy A356 Submitted to Ultrasonic Vibration

Figures 3 and 4 show the comparison of the obtained microstructure without "a, b, c" and with "d, e, f" the ultrasonic vibration. The eutectic Si phase "dark gray in the micrographs"

formed as acicular plate-like form. Particles with complex Chinese-script morphology "light gray in the micrographs" are Fe-bearing α-Al (Fe, Mn) Si intermetallic particles. The length of adendritic primary α-aluminium was about 550 μm and secondary arm was about 45 μm , as shown in Figure 4 a.

The coarse acicular eutectic silicon is exhibited in the untreated "without ultrasonic" A356 alloy "Figure 4 a". With application of ultrasonic vibration the size of the eutectic silicon changed to be finer and they had the trend to be broken into short sticks and small rounded as shown in Figure 3 d, e, and Figure 4 d, e.

The microstructure of α-Al was observed in a dendritic form and its average grain size was several micrometers. Upon the application of acoustic power, the dendritic structure was broken up into a somewhat globular grain structure or small polygonal as shown in Figure 3 d and Figure 4 e.

Recent research suggests that complex Chinese-script type Fe-aluminide particles can reduce ductility in Al–Si alloys as crack propagation occurs unhindered along the elongated branches of the complex particles. Major microstructural changes observed around the ultrasonic horn are expected due to high energy transfer in this region. Ultrasonic induced modification of solidification microstructure is largely dependent on cavitation and acoustic streaming effects [13].

The average ultrasound energy transmission rate through unit propagation area is expressed as [14],

$$I = \frac{1}{2}\rho c(2\pi f A)^2 \qquad (1)$$

Where ρ is the density of melt, c is the propagation velocity of sound, f and A are the frequency and amplitude of ultrasound, respectively. Estimating c as 1.3×10^3 ms^{-1} , A_{max} as 25 μm and f as 22.4 kHz and ρ_{Al} as 2.385 g cm^{-3} , energy transmission in the present experiments can be estimated as 2000Wcm^{-2}. The selected power output is well above the requirement for effective ultrasonication, where high intensity ultrasonication generally

employs $I \geq 100 Wcm^{-2}$ reported cavitation threshold in Al melt [13, 15]. Due to commercial impurity in the melt of A356 used in the present study, the threshold for initiation of cavitation is further increased. Consequently, prolific cavitation is responsible for the observed microstructure modification around the ultrasonic horn. Collapsing cavitation bubbles are stated to generate shockwave pulses of 1000 atm and microjects of $100 ms^{-1}$ [3]. This can alter the nucleation and growth behavior of solid. Beyond the region of maximum microstructural modification "stated above" surrounding the horn, observed changes gradually diminished with distance from the ultrasonic radiator.

The SEM photographs of the samples are shown in Figure 5. The dendritic shape of α-aluminium alloy A356 light grey is exhibited in the untreated alloy "Figure 5a & c".

With applying ultrasonic vibration at power 3.2 Kw, the size of the α- aluminium became much smaller and they had the trend to be broken into short polygon "Figure 4d, e". The microstructure of primary aluminum became refined and globular with ultrasonic vibration Figure 4a while the size of it was finer. The exact effect of ultrasonic on heterogeneous nucleation is largely debated. A researcher [3, 16] reported that the one argument states that forced wetting of insoluble inclusions would augment heterogeneous nucleation under cavitation. Ultrasonic vibration enhanced wetting of oxide particles has been demonstrated in Al–Mg alloy melt. It is well known that the nucleation efficiency of substrate particles is inversely related to the observed nucleation undercooling. While forced wetting of inclusions is likely to increase possible nucleation sites in the melt [13]. It has also been suggested that rapid adiabatic expansion of partially filled cavitation bubbles during the rarefaction phase may lead to undercooling at the bubble–melt interface resulting in nucleation events [8]. On the other hand, Das et al [13] argued that the total cooling possible during the life of bubbles is limited, although the rate of cooling may be high.

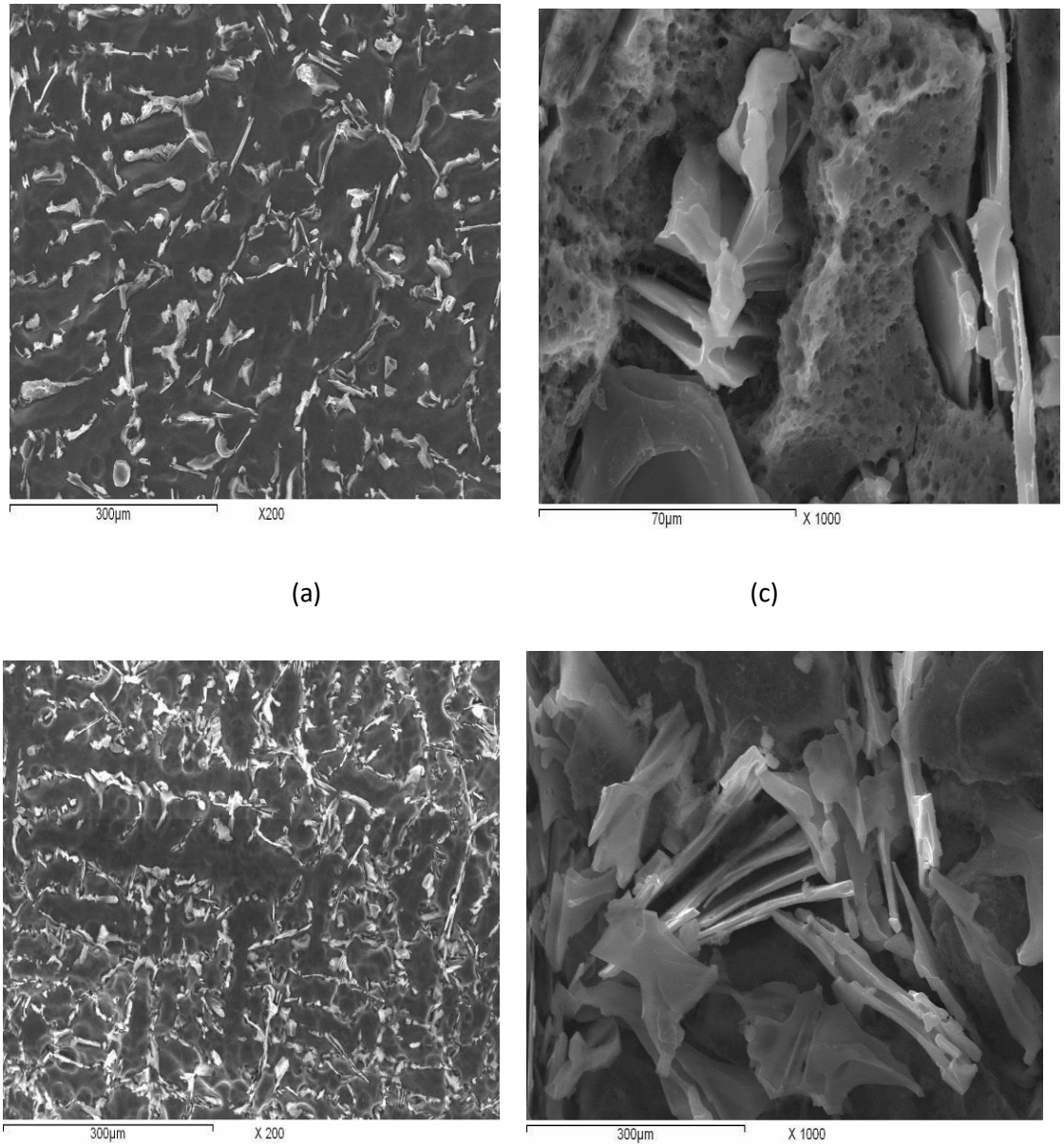

Figure 5. SEM image of the A356 alloy at mould temp. 200 °C without ultrasonic vibration, (a, c), with ultrasonic vibration b) 200X, d) 1000X. Deep etched.

The SEM photographs of the samples are shown in Figure. 5. The coarse acicular eutectic silicon is exhibited in the untreated alloy "Figure 5 a, c". With applying of ultrasonic vibration, the size of the eutectic silicon became much finer and should the trend to be broken into short sticks, which was in accordance with many researchers [2, 3, 12, 13,]

"Figure 5 b, d" The formation of eutectic silicon usually starts with the formation of Al-rich spikes and consequently the formation of localized Si enrichment within interdendritic liquid and segregation of numerical small Si needles, as can be used as base particles of β-Al_5FeSi. Ultrasonic cavitation can induce pressure fluctuation in the liquid pool and increase the wettability between impurity particles and liquid [17], which is advantageous to the nucleation of eutectic Si. Ultrasonic vibration can increase the probability of formation of eutectic nucleation within the interdendritic liquid, and the eutectic silicon is finer correspondingly. Ultrasonic vibration can cause pressure fluctuation in the melt and increase melting point of the fluid [13], very fine eutectic silicon is obtained. Two mechanisms explaining the effect of ultrasonic vibration on grain refinement cavitation-enhanced heterogeneous nucleation and acoustic streams that develop during cavitation and promote the distribution of nuclei throughout the melt, it leads to homogeneous distribution of silicon phase and α-aluminium through the alloy, so the combined effect of these two factors strongly increased the efficiency of ultrasonic vibration grain refinement.

A series of microstructure of investigated samples were quantitatively analyzed. The obtained results showed that without ultrasonic vibration, the average length of eutectic silicon was about 33.7 μm, and the average width was 4.4μm for a special poured in preheated mould at 200 °C. The aspect ratio was about 8. With ultrasonic vibration, the average length and width as shown in Table 3 were about 2.1μm and 1.9μm, respectively, and the aspect ratio could be considered as 1. Comparing the aspect ratios, the eutectic silicon was significantly refined and became small polygonal or fibres structure under ultrasonic vibration.

4. Conclusion

1. The primary aluminum in A356 alloy is significantly refined and globular grain was observed under ultrasonic vibration for sample poured in preheated mould at 200 °C.
2. The eutectic silicon is also refined and modified from coarse acicular plate-like to fine rod-like or finer rods under ultrasonic vibration.

3. The mechanism of the solidification of A356 alloy under ultrasonic vibration is referred to the combination of ultrasonic cavitation and acoustic streaming lead to the refinement of both primary aluminium and eutectic silicon as well.

5. References

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