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# Study on the Microstructure Changes of Hypereutectic Aluminum Casting Alloy Using Ultrasonic Vibration Process

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## Abstract

The microstructure changes using the ultrasonic vibration process method and Al-P refiner on permanent mold castings of hypereutectic aluminum alloy (Al-20Si) were studied using optical microscopy. The Al-P refiner refined the primary silicon phase from a large polyhedral shape to a smaller polyhedral shape, but had no effects on the morphology of the eutectic silicon phase. However, in samples subjected to ultrasonic vibration during the solidification process, both primary and eutectic silicon phases were significantly refined and modified respectively. Furthermore, the aluminum phase was also significantly changed. Small polyhedral silicon particles and globular aluminum grains were formed in the region near the probe (zone one). In the region far away from the probe (zone two), the primary silicon refined as in zone one, while the partly eutectic phase changed to globular alpha aluminum phase and polyhedral silicon phase.


## Introduction

Hypereutectic Al-Si alloys contain more than 12.7% Si, and are characterized by a discontinuous eutectic matrix containing primary silicon crystals of various sizes and shapes [1]. The presence of impurities in the metal, the cooling rate during solidification, and the refiner agents could determine the shape, size and distribution of the primary Si particles [2, 3]. With properties of lower coefficient of thermal expansion, high strength to weight ratio, and excellent wear resistance, the hypereutectic alloys are used for automotive pistons and engine block materials [4-6]. The high wear resistance is due essentially to the presence of the primary silicon crystals. However, the primary silicon usually forms non-uniformly throughout the sample. The most effective way to eliminate this problem is to refine the microstructure.

Phosphorous in the form of Al-P particles is often quoted as a good nucleate for silicon [3]. These particles are rejected by the growth dendrites and nucleate the eutectic cells on the growing dendrites [3, 7]. The injection of high intensity ultrasonic vibration into aluminum alloy during its solidification can eliminate columnar dendritic structure, refine the equiaxed grains, and under some conditions, produce globular non-dendritic grains [8]. The vigorous acoustic streaming in the eutectic liquid tends to dislodge Al-P particles at the existing dendrite interfaces and disperse them uniformly in the eutectic liquid [2, 9]. The removal of these Al-P particles from the dendrite interfaces prevents the nucleation of silicon particles on the dendrites, leading to the independent nucleation of the eutectic cells in the remaining liquid between dendrites [2, 9]. Some of the experiments performed on the influence of the ultrasonic vibration on the hypoeutectic alloys [10, 11]. Some of the paper focused on the ultrasonic effects on aluminum alloy before the casting [6]. The aims of this study were to evaluate the effect of high intensity ultrasonic vibration on Al-20Si aluminum alloy during the entire solidification process, and to compare the microstructure changes with the conventional Al-P refiner added sample and control sample.

## Experimental Method

The experimental setup consisted of an ultrasonic generator, a transducer made of piezoelectric lead zirconate titanate crystals (PZT), an ultrasonic horn (Ti-6Al-4V alloy), and an ultrasonic radiator/probe (Ti-6Al-4V alloy). The power output was up to 1500 watts by adjusting the output acoustic amplitude from 24.3 to 81 micron, or 30% to 100% of the unit's upper limit, in this study 60% of output power was used. The vibration frequency of the ultrasonic equipment was 20 kHz. For ultrasonic vibration castings, the ultrasonic vibration probe (1.9 cm diameter) was placed through the hole at the bottom of the mold (inner dimension is 4.5 cm in diameter by 8 cm in height) so that ultrasonic vibration could be applied from the beginning of metal pouring to the very end of the solidification process; the probe contacted the molten aluminum alloy directly during the solidification stage. An Al-20Si was used for this study. The alloy is a hypereutectic alloy containing 20 wt% Si and 0.5 wt % Fe, with trace amount of Cu, Zn, etc. This alloy was made by mixing pure Al (99.9%) with an Al-52%Si master alloy. The as-received pure aluminum and master alloy were cut, melted and held in the furnace for half an hour at 800 ± 5 °C, to allow the complete dissolution of silicon particles in the melt. After that, the molten alloy was transferred into the ladle and the temperature measured. The molten was then poured into the steel mold at casting temperatures of 735 (50 degree C above the liquidus), 700 (15 degree C above the liquidus) and 675 (10 degree C below the liquidus) degree °C [12]. Control samples were cast at the same conditions but without ultrasonic vibration. In this study, the conventional Al-P refiner was added into the molten aluminum alloy and the alloy was cast within 1 hour to avoid fading. The Al-P refiner was added by the Al-Si-P master alloy, which has 4.6%P, 3.1%Si, 2.3% Fe, 0.4%Mn and other elements comprising less than 0.18% in total. The total content of phosphorus in the cast sample was 0.1% [1, 13]. The casting conditions were the same as the control samples and ultrasonic vibration samples as given before.

Each sample was approximately 200 grams in weight, the largest diameter of the sample was 4.5 cm, and the height was about 7 cm. The shape of the cut sample was as illustrated in Figures 1. The as-cast specimens were cut vertically in half, which meant the direction was parallel to the symmetrical axis. In this section, all the characteristics of zone 1 (the small area near the ultrasonic vibration probe) and zone 2 (the large area far away of the probe) could be observed clearly, as well as the transient transition area (figure 1). For metallographic figure observation of the microstructure and particle size of the primary silicon, the specimens were sectioned, ground, and polished directly from the as cut specimen and prepared following the standard metallographic procedures. The polished specimens were etched in a modified Murakami etchant (60 mL H2O, 10 g NaOH, and 5 g K3Fe(CN)6) to reveal the microstructures of the samples [14].

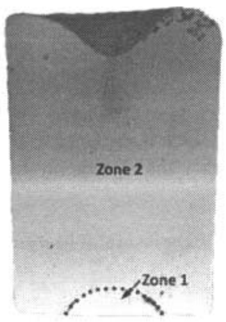


Figure 1 Vertical section of the ingot. Zone one: near the ultrasonic vibration probe; zone two: far away of the probe.

**Results and Discussion**

The Al-20Si alloy consists of three main phases in this study: primary silicon, alpha aluminum around the primary silicon, and the eutectic phase. Figure 2 shows the microstructure of the control sample at different casting temperatures (two of them were above the liquidus, the other one was below the liquidus) and at different positions of the sample (zone 1 and zone 2) in the steel mold. The micrographs on the left were from zone 1 and the micrographs on the right were from zone 2 (following figures are arranged in the same manner). The blocky shape shown in the images was the primary silicon that appeared before the eutectic reaction. Around the primary silicon, light dendritic like particles were alpha aluminum. The area beside the primary silicon and alpha aluminum was the eutectic region with plate like shape.

The microstructure of the two zones showed some differences (figure 2). In zone 1, there was less alpha aluminum phase around the primary silicon than in zone 2, and the size and amount of the primary silicon was also smaller in zone 1 than in zone 2. Because of a slower cooling rate in zone 2, the primary silicon had more time to grow, and this become larger. If the silicon grew from the liquid, the local equilibrium of the liquid concentration changed to lower Si percentage. In addition, a large amount of the alpha aluminum grew from the primary silicon particles, if the convection or the diffusion of the liquid were not intensity. The casting temperature also influenced the size and amount of primary silicon particle and the surrounding alpha aluminum in zone 2. At a higher casting temperature, the primary silicon turned to large size and the alpha aluminum turned to a much more developed dendrite like shape. The higher the casting temperature was, the longer the solidification time needed. This reason could give more time for primary silicon particle and nearby alpha aluminum to grow. However, in zone 1, the primary silicon and eutectic structure changed little, because of the high cooling rate in this region (the heat could be drag out from the bottom and side wall).

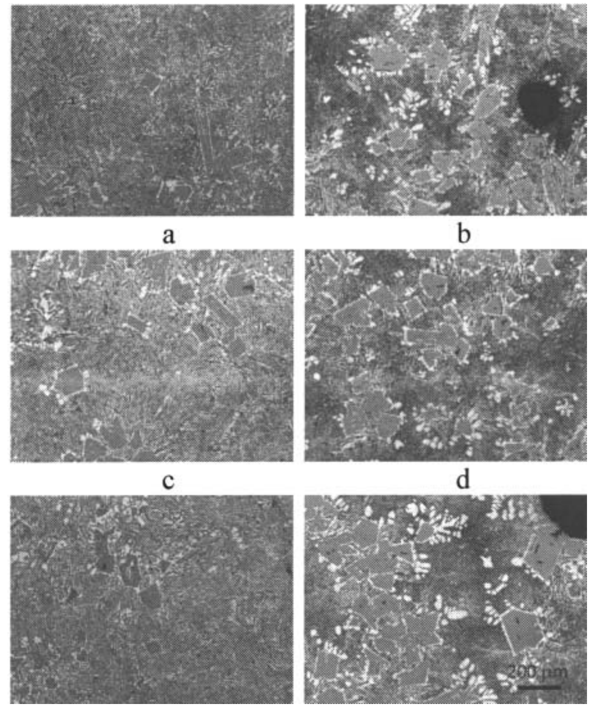


Figure 2 As-cast microstructure of Al-20Si ingot in zone one (left column) and zone two (right column). (a-b) 675 degree C; (c-d) 700 degree C; (e-f) 735 degree C. (100X)

Figure 3 shows the Al-P refiner treated Al-20Si alloy at three temperatures in both zones. The microstructure differences in zone 1 and zone 2 were not as distinctive when compared with the control sample. Both areas had three phases as mentioned above. This meant, the microstructure in the whole sample (zone 1 and zone 2 included) solidified uniformly after the Al-P refiner was added (the differences between zone 1 and zone 2 were small). Compared with the control sample, the size of primary silicon was smaller, but the number of silicon particles was greater. The alpha aluminum phases in these samples were also smaller than in the control sample. The eutectic phase did not change much compared with the primary silicon and alpha aluminum phases, and had plate like shape.

In these modified samples, the Al-P refiner provided a large number of nuclei during the solidification process. The primary silicon could nucleate on these Al-P nuclei, because of similar lattice parameters [7]. Therefore, at the beginning of the solidification stage, there were many primary silicon particles that grew from the nuclei. After the molten aluminum solidified, the sample had a lot of primary silicon particles. The same casting parameters as the control sample, the total amount of primary silicon should not change much compared with the control sample. Therefore, small size, but a large number of primary silicon could be obtained with added Al-P refiner. The alpha aluminum phase usually formed with the primary silicon phase, this means the size, shape, and number of alpha aluminum phase could be determined by the primary silicon. In the modified sample, the alpha phase was a small, non-well developed dendrite shape. With different casting temperatures, the shape of the alpha aluminum phase was slightly different. Due to the same tendency as discussed previously, higher casting temperature produced stronger dendrite or broken dendrite arms of alpha aluminum phase.

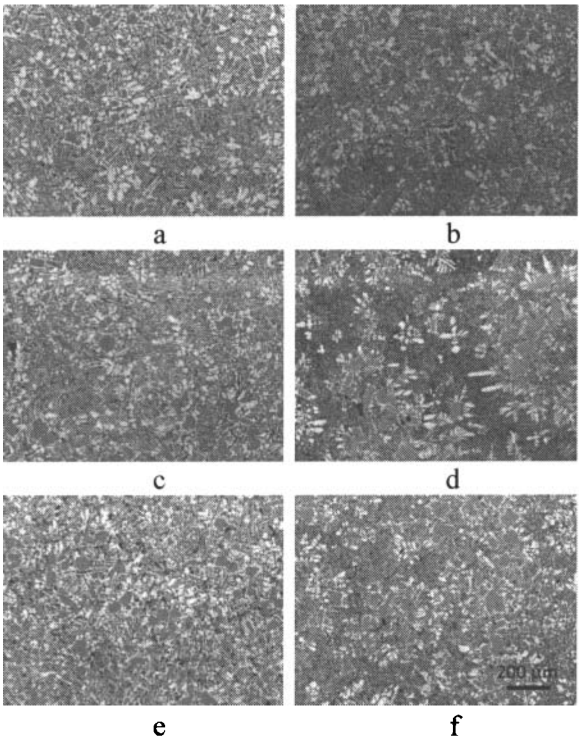

Figure 3 Phosphorus modified microstructure of Al-20Si ingot in zone one (left column) and zone two (right column). (a-b) 675 degree C; (c-d) 700 degree C; (e-f) 735 degree C. (100X)

Figure 4 shows the Al-20Si that was treated with ultrasonic vibration during the solidification process. Significant changes in the microstructure can be seen in the figure 4. Due to the attenuation of ultrasonic vibration, the ultrasonic vibration intensity in zone 2 was weaker than in zone 1. In figure 4, strong influences by the varying intensity of ultrasonic vibration in the microstructure could be seen by comparing zone 1 with zone 2.

In zone 1, there were mostly very fine globular α aluminum grains, blocky silicon with polyhedral shape along the grain boundary, and also eutectic silicon plates along gain boundaries. The polyhedral shaped silicon was the primary silicon phase. In Zone 2, the size of the polyhedral silicon particles were larger than that in zone 1. The alpha aluminum grains were still globular but not as spherical as those in Zone 1, and most of the alpha aluminum phases were located around the primary silicon phase. The eutectic silicon plates in Zone 2 were larger than that those in Zone 1.

Compared with the control sample and the Al-P modified sample, the microstructure of eutectic phase in the sample subjected to ultrasonic vibration changed completely in zone 1, from the plate like shape to fully divorced shape. In zone 1, the eutectic cell was hardly to find out. The big, block like primary silicon was broken down to very small size, with only a little proportion of the eutectic phase rejected and located along the grain boundaries. In zone 2, the microstructure of the sample also changed greatly when compared with the control sample and modified sample. The total area of eutectic cell was decreased. The size of the primary silicon was made smaller, while number particles were increased. The alpha aluminum changed from broken dendrite or dendrite shape to spherical shape, and unlike the control sample, the spherical alpha aluminum phase was not formed nearby the primary silicon. Therefore, the number and size of the alpha phase could not be determined by the primary silicon. At different casting temperatures, the grain size of globular alpha phase in zone 1 increased as the casting temperature went up, with an average of 18 micron at 675 degree C, 22 micron at 700 degree C, and 25 micron at 735 degree C. There was the same tendency on the size of primary silicon phase, alpha aluminum, and eutectic cell in zone 2.

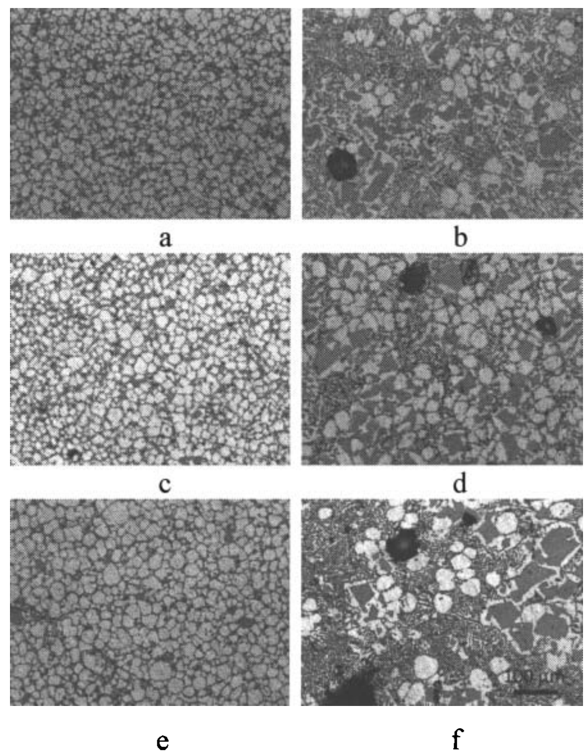

Figure 4 Ultrasonic vibration treated microstructure of Al-20Si ingot in zone one (left column) and zone two (right column). (a-b) 675 degree C; (c-d) 700 degree C; (e-f) 735 degree C. (200X)

Experimental results obtained in Al-20Si alloy have demonstrated that the application of high intensity ultrasonic vibration can turn larger eutectic cells into much smaller globular grains surrounded by primary silicon. Furthermore, high intensity vibration can be used to alter the morphology of the eutectic silicon and, more surprisingly, eliminate eutectic cells in zone 1.

Nonlinear effects can be produced by high-intensity ultrasonic vibration such as cavitation, acoustic streaming, and radiation pressure in the molten alloy. Acoustic streaming is a kind of turbulent flow. Cavitation, which means the formation of small cavities in the liquid, occurs as a result of the tensile stress produced by an acoustic wave in the rarefaction cycle. These cavitation cavities continue to grow by inertia until they collapse under the action of compressive stresses during the compression half-period, producing high-intensity shock waves in the fluid. These nonlinear effects (shear stress) ought to have major effect on the nucleation and the growth stages of the primary aluminum phase as well as the eutectic phases [15].

The influence of the ultrasonic vibration on this study was the changing of solidification mode during the ultrasonic vibration process. As mentioned above, the cavitation induced by ultrasonic vibration could introduce a lot of nuclei near the probe. These new formed nuclei could be distributed throughout the sample by acoustic streaming. Therefore, it could be seen that many primary silicon particles solidified in zone 2, and alpha aluminum phase in zone 2 was caused by the reduced Si concentration in the remaining liquid. The acoustic streaming could also reshape the phases in zone 2, by streaming means of the turbulent flow, which could break the alpha aluminum dendrite in the liquid and form the globular alpha phase. In zone 1, the ultrasonic vibration probe could provide high level energy through the liquid, thus this area seemed to solidify last. The concentrate of remaining liquid went to the eutectic point after a great amount of primary silicon formed. Therefore, zone 1 showed the microstructure of eutectic content liquid formed under ultrasonic vibration. The characteristics of the microstructure in this area were consistent with our former study. The formation of primary silicon particles around the spherical aluminum phase in zone 1 could be related to a divorced eutectic formation under the influence of high intensity ultrasonic vibration.

## Conclusion

Two zones with distinct microstructure were identified in an ingot subjected to ultrasonic vibration. Zone 1 occurred near the ultrasonic probe that was in direct contact with the solidifying ingot. Spherical alpha aluminum phase surrounded with small primary silicon particles could be formed in the Al-20Si alloy, instead of large primary silicon and eutectic phase, through the application of high intensity ultrasonic vibration during the solidification process. Zone 2 occurred past zone 1, away from the ultrasonic probe. The size of the primary silicon particles and eutectic cell were also reduced in samples subjected to high intensity ultrasonic vibration. The microstructure was totally changed in zone 1, and the aluminum grains were generally smaller in zone 1 than that in zone 2. More primary silicon particles were formed in zone 1 than that in zone 2.

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