The ultrasound effects on the formation of the solidification structure of A356 ingots processed via a 2-zone induction melting furnace

A Dong and L Nastac
The University of Alabama, Tuscaloosa, AL, 35487, USA
E-mail: lnastac@eng.ua.edu

Abstract. To study the formation of the solidification structure including the columnar-to-equiaxed transition (CET) under the influence of ultrasound, a 2-zone furnace system and an ultrasound equipment were utilized. The 2-zone furnace system consists of an induction furnace with a top coil and a bottom coil, a graphite crucible, and a water-cooled chill block located at the bottom of the crucible. By controlling both the top and bottom coil output power independently, the furnace can create various temperature gradients and cooling rates in different regions of the graphite crucible. The ultrasound probe was inserted at the top of the crucible. The top of the crucible was also thermally insulated. Temperature measurements were performed at different locations in the crucible. Optical microscopy was used to characterize the microstructure of the A356 cylindrical ingots. The effects of ultrasound on the microstructure formation during solidification of A356 alloy was studied. A numerical model was developed to compute the temperature gradients and mushy zone evolution in the crucible and to assist in developing of solidification maps.

1. Introduction
The need for lightweight high-performance structural components is expected to continuously increase as automotive, military and aerospace industries are required to further improve the energy efficiency, safety and reliability of their products. Aluminium, magnesium or titanium alloys being much lighter than steel are attractive replacement materials and so there is great interest in enhancing their properties [1-4]. It has been proved that by applying the ultrasonic technology (UST) to molten metal processing columnar dendritic structures can be eliminated and globular non-dendritic structures can be achieved [5-7]. The nonlinear effects like cavitation and acoustic streaming introduced by the ultrasonic field could significantly affect the heat and mass transfer of the solidifying A356 alloy, transforming the grain morphology from dendritic to globular, decreasing the grain size and modifying their properties [8]. UST could also induce degassing during the cavitation process, by creating small hydrogen bubbles that will escape from the molten metal. The pressure oscillations under UST processing can produce large temperature gradients in the liquid, which enhance the nucleation intensity of the bubble. The convection and shock waves produced by UST may promote dendrite fragmentation [9-11]. It is also demonstrated that UST would be more effective when the application temperature is below the liquidus temperature of the alloy [12-13].

In order to create the mushy zone and controlled solidification and cooling conditions, a 2-zone furnace with two separated coils was adopted. By adjusting the top and bottom coil powers of the 2-zone furnace independently, it is possible to create distinct temperature gradients in the crucible with a
range of 1 ~ 104 K/m. Cooling rates with a range of 0.005 ~ 0.5 K/s can also be produced in the crucible. Note that the crucible is made of graphite with a water-cooled chill block at the bottom. The 2-zone furnace makes it possible to control the mushy zone size and the grain growth rate during the solidification process.

This study has three main objectives: (1) Compare the solidification process and cooling curves of A356 alloy with and without UST at different cooling rates by controlling the top and bottom coil power levels; (2) Analyse the solidification structure of the A356 alloy at different ingot positions with and without UST; (3) Develop and validate a numerical model to simulate the solidification process and the UST refinement of the A356 microstructure. The results include the temperature profiles and cooling curve analysis, which are also verified by the current experimental work. Microhardness at different positions and for different solidification conditions were compared as well.

2. Experiment description
In the present work, a commercial aluminium alloy A356 was used. A schematic diagram of the two-zone furnace is shown in figure 1(a). The system parameters are as follows: maximum power of the top/bottom zone is 10 kW; height between bottom coil and base is 83 mm; height of top/bottom coil is 152 mm; gap between the top and the bottom zone is 32 mm; total height of the furnace is 425 mm. A graphite crucible opened at both ends with the height, the exterior and the interior diameter of 355, 100, and 75 mm, respectively, was used in the two-zone furnace system. The top of the crucible is covered by a ceramic cap. A water-cooled stainless-steel chill block was applied at the bottom of the furnace as a cooling system. The ultrasonic equipment parameters are as follows: maximum power 2.4 kW, frequency 18 kHz, the diameter of the Nb ultrasonic probe is 40 mm and the probe amplitude is 20 microns. Four K-type thermocouples were fixed at different positions inside the crucible to record the temperature change as a function of time, as shown in figure 1(b). Thermocouples 1, 2, 3 and 4 are located at 260, 190, 120 and 50 mm from the bottom, with wires sealed in ceramic tubes to protect them from the molten alloy.

![Figure 1. (a) Sketch of two-zone furnace system and (b) thermocouples positions with initial cooling temperatures](image)

Two different groups of experiments were carried out: (1) Non-UST processing, which is named the control group experiment (N0 group, top and bottom coils without power during cooling), N1 group (top 2 kW and bottom 4 kW during cooling), N2 group (top 3 kW and bottom 6 kW during cooling) and N3 group (top 4 kW and bottom 7 kW during cooling); (2) UST processing group (UST group, top and bottom coils without power during cooling). In the non-UST groups experiment, 3.3 kg of A356 alloy was melted in the two-zone furnace. Then, four ceramic coated thermocouples were inserted into the designed positions, as shown in figure 1(b), to record the temperature change as a function of time. The top/bottom zone output power values were adjusted to create the desired temperature gradient in the furnace. Firstly, the top and bottom zone output powers were adjusted to the maximum values until the top melt reached about around 730 °C (thermocouple 4), then the melt in the furnace was cooled down...
by different cooling conditions to the room temperature. In the UST group experiment, the ultrasonic probe was inserted into the melt at about 25 mm below the surface, and the same procedure as explained above was used. After the top melt reached about 730 °C, the furnace was switched off and the ultrasound generator was turned on until the top melt temperature decreased to about 620 °C and then it was shut down and taken out from the melt.

The processed cylindrical cast ingots with a height of 275 mm were cut into 16 disks. Each disk has a height of about 17 mm. Then, these samples were mechanically grounded by #300, 600, 800 and 1200 grinding papers respectively and polished with 3 and 1 μm diamond polishing agents. Finally, the microstructure of the cast samples was characterized via Optical Microscopy by using a Nikon Model Epiphot 200. The microhardness of the specimens was obtained through a Vickers hardness indenter (Buehler Inc.) with a load of 500 gf and dwell time of 15 seconds. Five locations were tested, and the average value was considered as the microhardness.

2.1. Cooling curve comparison

The cooling curves of the all groups are shown in figure 2. The equilibrium liquidus temperature of A356 alloy is about 617 °C. The comparison of non-UST groups from figures 2(a) to 2(d) shows that by adjusting the power of the two coils during solidification, it is possible to control the cooling rates and temperature gradients and create mushy zones with different depths. In addition, due to different cooling rates and temperature gradients, the eutectic solidification process at location 1 is much longer than in location 2, 3 and 4 for the non-UST groups. From figure 2(e), the comparison of N₀ and UST group shows some major differences between these two curves. First, the temperature of the control group drops faster than that of the UST group. Because of the UST application, there is an additional heat source term, which is explained in previous work [14]. Second, the cooling curves of the UST group is smoother during the eutectic stage. The acoustic streaming and cavitation effects due to UST refined the Al matrix and the Si eutectic phase. In addition, by comparing both groups, the heat and fluid flow effects caused by the UST also decreased the temperature gradient in the crucible, which is also indicated by the microstructures shown in figures 3-6.

![Figure 2](image-url)

**Figure 2.** Cooling curves of (a) non-UST groups comparison of location 1; (b) non-UST groups comparison of location 2; (c) non-UST groups comparison of location 3; (d) non-UST groups comparison of location 4; (e) non-UST N₀ group and UST group comparison
From table 1, the largest temperature gradient occurring at location 4 is ~ 10000 K/m and the range of local solidification time is 100 ~ 20000 s, which are both beneficial to create different growth rates and microstructures. In table 1, the $G_{TL}$ is temperature gradient before liquid solidification, $V$ is solidification rate, $C_R$ is cooling rate and $T_f$ is local solidification time. By controlling the cooling rates and the temperature gradients in the mushy zone, different microstructures can be achieved (see the microstructures shown in figures 3-6). By comparing the non-UST groups of $N_0$ to $N_1$, from the above analysis results of figures 3-6, it can be shown that with the decrease of cooling rates, the grain size becomes larger, and the largest grain size could reach about 1.5 mm. In addition, the grain size decreases from location 1 to 4. The reason is that the temperature gradients in the locations 3 and 4 are much larger than in the locations 1 and 2. Also, the high cooling rates caused by the chill block located at the bottom of the crucible cause the microstructures in the location 4 to be more uniform and finer than in the other regions. By comparing UST with $N_0$ group, there is an obvious much smaller CET region under the influence of the UST.

Table 1. Analysis results for the non-UST groups and the UST group cooling curves

| Location | $G_{TL}$ (K/m) | $T_f$ (s) | $C_R$ (K/s) | $V$ (m/s) |
|----------|----------------|----------|-------------|-----------|
|          | $N_0$ group    | $N_1$ group | $N_2$ group | $N_3$ group |
| L1       | 37.1           | 7.14     | 4.3         | 2.9       |
| L2       | 57.1           | 100      | 45.7        | 29        |
| L3       | 485.7          | 771.4    | 428.6       | 185       |
| L4       | 8900           | 8900     | 8900        | 8900      |
| L1       | 544            | 548      | 1384        | 4,166     |
| L2       | 464            | 454      | 1060        | 2942      |
| L3       | 278            | 274      | 821         | 1926      |
| L4       | 166            | 164      | 328         | 667       |
| L1       | 1.18E-01       | 1.17E-01 | 4.62E-02    | 1.54E-02  |
| L2       | 1.38E-01       | 1.41E-01 | 6.04E-02    | 2.18E-02  |
| L3       | 2.30E-01       | 2.34E-01 | 7.80E-02    | 3.32E-02  |
| L4       | 3.86E-01       | 3.90E-01 | 1.95E-01    | 9.60E-02  |

2.2. Microstructure analysis

Figure 3. Microstructures of specimens from location 1 of the cast ingots (N-labelled specimens are from the non-UST group, U-labelled specimens from the UST group and Nc specimens from cross section of $N_0$ group).
Figure 4. Microstructures of specimens from location 2 of the cast ingots (N labelled specimens are from the non-UST group, U-labelled specimens from the UST group and Nc specimens from cross section of N0 group).

Figure 5. Microstructures of specimens from location 3 of the cast ingots (N-labelled specimens are from the non-UST group, U-labelled specimens from the UST group and Nc specimens from cross section of N0 group).

Figure 6. Microstructures of specimens from location 4 of the cast ingots (N labelled specimens are from the non-UST group, U-labelled specimens from the UST group and Nc specimens from cross section of N0 group).
In addition, it can be seen from figures 3-6 that the eutectic is more refined and modified in the UST case. From location 1 to 3, the UST transforms the morphology of the grains from dendritic to globular. Table 2 presents the detailed solidification analysis data and the microstructural characteristics of different groups. In table 2, the GZ is grain size, GD is grain density, SDAS is secondary dendrite arm spacing, SA is silicon area and SR is silicon roundness in eutectic. The size of the microstructures in table 2 were calculated by averaging at least 5 different measured values. Table 3 shows that the UST group has a smaller CET size than the non-UST N0 group. The CET size measurements in table 3 include the mixed columnar and equiaxed region. Also, the increase in the top and bottom coil power will decrease the CET size. The microstructure (primary phase and silicon in the eutectic phase) of the UST group is finer than that of the non-UTS groups. Figure 7 further proves that, due to the acoustic streaming and cavitation effect, the UST group has a much refiner microstructure than that of the non-UST groups.

Table 2. Experimental measurements for the non-UST control groups and the UST group

| Locations | Group | GZ [µm] | GD [nuclei/m³] | SDAS [µm] | SA [µm²] | SR [%] |
|-----------|-------|---------|---------------|-----------|----------|--------|
| 1         | UST   | 410     | 1.45E+10      | 105       | 29       | 30.5   |
|           | N0    | 780     | 2.11E+09      | 140       | 42       | 18.3   |
|           | N1    | 720     | 2.68E+09      | 147       | 48       | 19.2   |
|           | N2    | 840     | 1.69E+09      | 236       | 36       | 13.4   |
|           | N3    | 920     | 1.28E+09      | 328       | 24       | 8.2    |
|           | N1    | 1513    | 2.89E+08      | 579       | 14       | 5.3    |
| 2         | UST   | 353     | 2.27E+10      | 73        | 16       | 53.2   |
|           | N0    | 634     | 3.92E+09      | 95        | 21       | 38.4   |
|           | N1    | 720     | 2.68E+09      | 98        | 20       | 41.2   |
|           | N2    | 581     | 5.10E+09      | 187       | 33       | 28.7   |
|           | N3    | 565     | 5.54E+09      | 249       | 22       | 24.3   |
|           | N4    | 1124    | 7.04E+08      | 361       | 13       | 11     |
| 3         | UST   | 280     | 4.56E+10      | 56        | 8        | 74.3   |
|           | N0    | 470     | 9.63E+09      | 74        | 11       | 55.1   |
|           | Nc    | 466     | 9.88E+09      | 74        | 11       | 54.9   |
|           | N1    | 550     | 6.01E+09      | 145       | 14       | 41.2   |
|           | N2    | 643     | 3.76E+09      | 167       | 15       | 35.1   |
|           | N3    | 935     | 1.22E+09      | 223       | 9        | 10.6   |
| 4         | UST   | 212     | 1.05E+11      | 53        | 11       | 27     |
|           | N0    | 198     | 1.29E+11      | 49        | 15       | 43.6   |
|           | Nc    | 221     | 9.26E+10      | 53        | 12       | 41     |
|           | N1    | 521     | 7.07E+09      | 186       | 5        | 47     |
|           | N2    | 591     | 4.84E+09      | 243       | 6        | 35     |
|           | N3    | 884     | 1.43E+09      | 352       | 8        | 19     |

Table 3. Size of CET (mm) for the non-UST control groups and the UST group

| Group  | UST | N0 | N1 | N2 | N3 |
|--------|-----|----|----|----|----|
| From ingot top | 17  | 53 | 22 | 15 | 7  |
| From ingot bottom | 23  | 75 | 29 | 20 | 13 |

Figure 7. Comparison of microstructures of N0 and UST samples at location 3 (500×)
2.3. Microhardness results

The Vickers hardness test (Figure 8) shows that the micro-hardness is related to the grain size and silicon roundness in eutectic. The smaller grain size and the larger silicon roundness in eutectic, the higher microhardness would be. Due to a good refining of the microstructures by the UST acoustic streaming and cavitation effects, the UST group has the highest microhardness performance. In addition, by comparing with the columnar direction, the cross section of N₀ group has a better performance in microhardness.

3. Modelling results

ANSYS’s Fluent has been applied to simulate the fluid flow and solidification process in the two-zone furnace. The modelling parameters are as follows: height and diameter of the graphite crucible are 305 and 75 mm respectively, alloy thermal conductivity is 90 W/(m*K) at T₁ and 150 W/(m*K) at T₃[15], alloy viscosity is 0.03 kg/(m*s), the solidus temperature (Tₛ) and liquidus temperature (Tₐ) are 565.0 °C and 617 °C, respectively. The alloy density is a piece-wise linear relationship with the temperature, varying from 2547 kg m⁻³ at Tₛ to 2423 kg m⁻³ at Tₐ. The outlet at the right corner of the top cover of the crucible is set as pressure-outlet. The bottom and top coils are mixed (convention and radiation) wall type with a heat transfer coefficient of 10 W/(m²*K) and an emissivity coefficient of 0.9. External radiation temperature was measured in these experiments as 150 °C. All other walls are set up as zero heat flux. Simulation time is about 1500 s for N₁ group, 6250 s for N₂ group and 20000 s for N₃ group. The previous work has shown that this model can successfully predicts the solidification process of the N₀ group [16]. Figures 9-11 show the initial temperature contours, which are the same for all groups, i.e., 757 °C at the top and 598 °C at the bottom. The initial large temperature gradient in the liquid is helpful to create a large mushy zone during the solidification/cooling process. The predicted temperature evolution, local cooling rate and solidification time compared well with the experimental data.
4. Concluding remarks

An experimental system consisting of a 2-zone furnace with UST has been set up successfully in this work, making possible to refine and modify the microstructure of unidirectionally solidified A356 ingots. The solidification parameters of both the non-UST and the UST cases as well as the microstructures of the processed samples were compared. The results show that the UST is valuable in refinement and modification of the A356 microstructure. The ANSYS’s Fluent was used to predict the solidification process of the A356 melt in the two-zone furnace under non-UST conditions. Cooling curve analysis was also performed. The simulation results compare well with the experimental measurements and reveals in more detail the solidification parameters of the carried-out experiments. In a future study, to clearly understand the UST refining mechanism during the solidification process, a CFD model for the 2-zone furnace with UST will be developed and implemented into Fluent.

References

[1] Kaczmar J W, Pietrzak K and Wlosinski W 2000 J. Mater. Process. Tech. 106 58-67
[2] Durisinova K et al. 2012 J. Alloys Compd. 525 137-42
[3] William C H 1998 Mater. Sci. Eng. A 244 75–9
[4] Zhang D and Nastac L 2014 J. Mater. Research. Tech. 3 296-302
[5] Eskin G I 2002 Zeitschrift fuer Metallkunde. 93 502-7
[6] Eskin D G 2017 Mater. Sci. Tech. 33 636-45
[7] Eskin G I 1998 Ultrasonic treatment of light alloy melts (CRC press)
[8] Nastac L 2011 Metall. Mater. Trans. B 42 1297-305
[9] Blundell S J and Blundell K M 2009 Concepts in thermal physics. (OUP Oxford)
[10] Hem S L 1967 Ultrasonics 5 202-7
[11] Stefanesco D M 2015 Science and engineering of casting solidification (Springer)
[12] Flores A et al. 1998 Intermetallics 6 217-27
[13] Puncreobutr C et al. 2014 Acta Mater. 79 292-303
[14] Xuan Y, Dong A and Nastac L 2019 Light Metals 1545-50
[15] Bakhtiyarov S I, Overfelt R A and Teodorescu S G 2001 J. Mater. Sci. 36 4643-8
[16] Dong A and Nastac L, “TMS 2020 149th Annual Meeting & Exhibition Supplemental Proceedings,” https://doi.org/10.1007/978-3-030-36296-6, The Minerals, Metals & Materials Series, 1117-26