Effects of Ultrasonic Stirring on Microstructures of Al-7wt%Si Alloy Ingot

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Abstract. The effects of ultrasonic stirring treatment on grain refining and improving the mechanical properties of Al-7wt%Si cast aluminium alloy were systematically investigated in this study. The microstructures and hardness features of the cast ingot specimens were characterized by X-ray diffraction (XRD), scanning electron microscopy (SEM), optical microscopy (OM), energy dispersive spectrometer (EDS), digital hardness tester, respectively. The investigation was found that the grains of the alloy were obviously refined after ultrasonic treatment. The average grain diameter of Al-7wt%Si alloy ingot was reduced from 395μm to 206μm resulted from the ultrasonic stirring and master alloy elements addition. In contrast, the hardness of the ingot specimen increased from 27HB to 37HB due to the ultrasonic stirring treatment. In fact, the tensile strength of the alloy was also increased because of the grain refinement and the degassing function of the ultrasonic stirring. The observation also revealed that some dispersed gas cavity was agglomerated in the upper part of the alloy ingot.

1. Introduction
Traditional metal casting aluminium alloys are widely used in aviation, aerospace, automotive machinery and other industries, owing to their low density and high specific strength [1]. Grain refinement is not only an important way to obtain high quality aluminium ingots, reduce segregation and improve the quality of aluminium metallurgy, but also an necessary measure of improving the casting Al-Si alloys mechanical properties which can help improve performance of the alloys [2]. The effect of grain refining on different aluminium alloys were achieved by ultrasound which can refine the melt microstructure through cavitations, acoustic streaming, radiation pressure and other physical effects [3-6]. Compared with electromagnetic stirring, ultrasonic stirring has the advantages of wide range of function stirring evenly and good degassing effect [7]. Ultrasonic stirring has a great effect on degassing and it can also help reduce inclusions and macroscopic segregation. The current researches focuses on the grain refinement and degassing of aluminium alloys melt by ultrasonic stirring [8-12]. The microstructures and gas cavity distribution of the ingot and the mechanical properties of the ingot were studied by adding a comparative experiment of different content of master alloys and ultrasonic stirring.
2. Experimental methods and equipment

The experimental device is composed of three major systems. The resistance furnace heating system consists of a well resistance furnace and a graphite-clay crucible (outer diameter of top is 121 mm, outer diameter of bottom is 83 mm, and height is 154 mm). The equipment of ultrasonic treatment system tracks frequency automatically and the actual work power is 150w. The temperature measuring system consists of temperature control recorder and thermocouple. The Al-7wt%Si alloy was prepared from industrial pure aluminium (99.7%) and pure silicon (95%). At the same time, a certain amount of Al5Ti1B master alloy was used in the experiment.

About 800 g of the industrial pure aluminium was melted and preheated to 760 °C inside a graphite-clay crucible, then held for 10 minutes. After removing the slag of the molten aluminium, adding pure silicon and holding it at 760 °C for 2 hours is a method for obtaining Al-Si alloy solution. For samples without the addition of master alloy, the graphite-clay crucible containing the molten Al-Si alloy was removed after reaching 720 °C and transferred to the ultrasonic treatment platform. For samples with the addition of master alloy, the different content of Al5Ti1B master alloy were introduced into the molten melt at 720°C, which then was mechanically stirred and held for 5 minutes before being transferred to the ultrasonic treatment platform. The ultrasonic probe is in the center position of the solution in the crucible, the depth is about 20 mm, and the ultrasonic treatment time is 4min. After ultrasonic treatment, the crucible is naturally solidified in the air. Table 1 shows the samples numbers and treatment methods.

| sample number | treatment method                      |
|---------------|--------------------------------------|
| 1#            | no treatment                         |
| 2#            | ultrasonic stir                      |
| 3#            | 0.2% master alloy and Ultrasonic stir|
| 4#            | 0.5% master alloy and Ultrasonic stir|
| 5#            | 1.0% master alloy and Ultrasonic stir|
| 6#            | 1.5% master alloy and Ultrasonic stir|
| 7#            | 0.2% master alloy                    |
| 8#            | 0.5% master alloy                    |
| 9#            | 1.0% master alloy                    |
| 10#           | 1.5% master alloy                    |

The samples were cut at the center of the cross section at 70 mm below the upper surface of the ingot. The size is 10mm × 15mm × 20mm. Firstly, the samples were analyzed, and then the hardness of the samples was tested. Lycra DM2500C optical microscope, Huayin digital Brinell hardness tester, Phenom desktop scanning electron microscope and Huayin Micro Vickers hardness tester were used to characterize the materials.

3. Results and discussion

3.1. Effect of ultrasonic stirring on microstructure of Al-7wt%Si alloy

It can be seen in figure 1 (a) that a large number of pores are distributed in the cross section of the ingot and the pores are distributed throughout the section of the ingot. The partial pressure of aluminium alloys were changed when the aluminium alloys melt were broken down into the cavities by the effects of the continuous destruction of ultrasonic cavitations and the hydrogen which lumped together by cavities was dissolved in the melt of aluminium alloy. When the pressure is low, the pores form tiny bubbles, and when the pressure rises, the bubbles were broken and the shock waves were generated. Therefore, the hydrogen gas which was diffused into the bubbles was precipitated with the
separation of the bubbles. It can be seen in the figure that the porosity of #2 sample of the cross section is much less than the ingot of the #1 sample and almost all of them are concentrated below the ultrasonic probe. Thus, the porosity of #2 sample is convenient for resection. Therefore, the effect of eliminating the melt pores was achieved by the ultrasonic stirring.

![Figure 1](image1.png)

**Figure 1.** Optic photos of Al alloy ingot (a) No treatment, (b) Treated by ultrasonic.

From figure 2 (a), it can be seen that the #1 sample has dendrite and coarse grain. The nucleation rate was increased significantly because of cavitations bubbles burst into instantaneous undercooling, when ultrasonic stirring was added to the aluminium alloy melt. At the same time, the acoustic stream causes a sharp lasing flow and shock wave, which can interrupt the growing nuclei and inhibit the growth of dendrites. Therefore, it can be seen in figure 2 (b) that the grain size of #2 sample is obviously refined, and the grain distribution is also very uniform. Therefore, the ultrasonic stirring has obvious effect on grain refinement. It can be seen from figure 2 (c) that the eutectic silicon phase of #1 sample is all flaky, and the aspect ratio of eutectic silicon phase is 17.2. The nucleation rate of liquid phase was increased and the growth of eutectic silicon phase was inhibited, so the eutectic silicon phase of #2 sample showed a block or round shape as shown in figure 2 (d) and the aspect ratio of eutectic silicon is 4.3. Therefore, the ultrasonic stirring also has a good deterioration affection the eutectic silicon phase.

![Figure 2](image2.png)

**Figure 2.** Microstructures of Al-7wt%Si alloy ingot (a) Optic photo of no treatment; (b) Optic photo of ultrasonic treatment; (c) SEM of no treatment; (d) SEM of ultrasonic treatment.

3.2. Effect of ultrasonic and Al5Ti1B master alloy on microstructure refinement of Al-7wt%Si alloy

Grain refinement was achieved by adding particles that can act as substrates for heterogeneous nucleation. From figure 5 and figure 6, the bright gray particles were confirmed as TiB2 which play an important role in grain refinement when the master alloy is added to the molten aluminium alloy [13]. There will be smaller formation of the organization when the more TiB2 particles which was the effective nuclei of grain heterogeneous nuclei are present in the crystal [14]. Thus, it can be seen from table 2 and figure 3 (e)-(h) that the average grain diameter decreases from 286.1μm to 250.4μm as the addition of the master alloy content increases. Therefore, the grain refinement effect is improved.
Figure 3. After ultrasonic and master alloy treatment of Al-7wt%Si alloy microstructure: (a) UT and 0.2% master alloy, (b) UT and 0.5% master alloy, (c) UT and 1.0% master alloy, (d) UT and 1.5% master alloy, (e) 0.2% master alloy, (f) 0.5% master alloy, (g) 1.0% master alloy, (h) 1.5% master alloy.

As shown in figure 4 (a) and figure 4 (b), the number of effective nucleation particles of the ingots with the addition of Al5Ti1B master alloy and ultrasonic stirring was increased, because of the high-frequency vibration of ultrasonic stirring can disperse the large TiB2 particles (the nucleation-inhibiting region) into a plurality of small TiB2 particles (the nucleation-promoting region) [15]. The ultrasonic stirring not only refines the grain but also improves the grain refining effect of the master alloy by increasing the nucleation ability of TiB2. From figure 3 and table 2, it can be seen that the average grain diameter of the #5 sample is improved by 57% compared with the 1# sample, and the average grain diameter of the #5 sample is 20% higher than that of the #2 sample. Therefore, the samples had a better effect when the Al5Ti1B master alloy while adding ultrasonic stirring was added.

Figure 4. SEM image of the TiB2 particles: (a) 1.0% master alloy, (b) UT and 1.0% master alloy, (c) UT and 1.5% master alloy, (d) EDS analysis results.
The nucleation ability of TiB$_2$ particle clusters are limited when the grain contains too much TiB$_2$ particle. When the power of ultrasonic stirring was fixed, increasing the amount of intermediate alloy will lead to the formation of too large TiB2 particles, and then reduce its nucleation ability. It can be seen from table 2 and figure 3(a)-(d) that the average grain diameter of the alloy decreases from 170.3μm to 164.7μm when the amount of the master alloy is increased from 0.2% to 1.0% under the condition of ultrasonic stirring. The effect of grain refinement is not obvious with the increase of adding amount, when the addition amount of master alloy is less than 1%. The refining effect becomes worse, when the amount of the master alloy is increased to 1.5%, and at the same time, it can be seen from figure 4 (b) and (c) that the metamorphic effect of eutectic silicon phase is also worse. Therefore, the addition of master alloy under ultrasonic stirring can obviously refine the grain size, but the increase of the amount of master alloy cannot improve the grain refinement effect.

**Figure 5.** XRD image of the #3-#6 samples.  
**Figure 6.** XRD image of the #7-#10 samples.

| Treatment methods                  | Maximum grain diameter/μm | Minimum grain diameter/μm | Mean grain diameter/μm |
|------------------------------------|---------------------------|---------------------------|------------------------|
| No treatment                       | 587.9                     | 240.1                     | 394.8                  |
| Ultrasonic stir                    | 322.5                     | 104.6                     | 205.6                  |
| 0.2% master alloy and Ultrasonic stir | 386.5                     | 86.4                      | 170.3                  |
| 0.5% master alloy and Ultrasonic stir | 376.4                     | 72.5                      | 168.4                  |
| 1.0% master alloy and Ultrasonic stir | 261.1                     | 69.7                      | 164.7                  |
| 1.5% master alloy and Ultrasonic stir | 327.6                     | 71.2                      | 174.4                  |
| 0.2% master alloy                  | 577.2                     | 159.9                     | 286.1                  |
| 0.5% master alloy                  | 564.4                     | 125.4                     | 265.8                  |
| 1.0% master alloy                  | 507.2                     | 136.6                     | 251.1                  |
| 1.5% master alloy                  | 363.9                     | 143.7                     | 250.4                  |
3.3. Effect of Ultrasonic and Al5Ti1B Master Alloys on Mechanical Properties of Al-7wt% Si Alloy

From figure 7, it can be found that the Vickers hardness increases as the average grain diameter decreases. The Brinell hardness does not follow the Hall-Petch relationship because the porosity was not eliminated completely. As can be seen in table 2 and figure 7, the average grain diameter of the #2 ultrasonic stirring sample was decreased 189μm relative to the #1 untreated sample, and the Brinell hardness increased by 15.5%. The average grain diameter of the #10 sample was decreased 145μm relative to the #1 sample, and the Brinell hardness is only 1% different because of the large amount of pores in the #10 sample. As the average grain diameter decreases there was no change in the hardness of the #10 sample. Therefore, ultrasonic stirring can increase the hardness of the material by eliminating the porosity.

4. Conclusions

(1) Applying ultrasonic stirring in the melt can reduce the gas cavity of the melt. At the same time, the hardness of the ingot metal increased from 27HB to 37HB;
(2) The ultrasonic stirring has the effect of grain refinement and eutectic silicon phase deterioration. After treatment, the average grain diameter of the grains decreased from 395μm to 206μm, and the aspect ratio of eutectic silicon phase decreased from 17.2 to 4.3;

(3) Adding proper amount of master alloy to the ultrasonic stirring can further refine the grains. Adding the master alloy under ultrasonic stirring can reduce the average grain diameter by 57%, indicating that the addition of the master alloy under ultrasonic stirring can significantly refine the grain of the aluminium alloy ingot, but the effect of grain on grain refinement is not obvious when increase the addition of the master alloy.

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