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Effect of Cooling Rate on Microstructure and Mechanical Properties in Al-Si Alloys

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Aluminum-silicon base alloys are widely used in aerospace structural application and the automobile industry due to their low thermal expansion coefficient, high wear resistance and good castability. They can be divided into hypoeutectic, eutectic and hypereutectic alloys according to the amount of silicon content. The morphology and size of primary silicon and eutectic silicon affect mechanical properties in Al-Si alloys. In this study, the micro-structural variation of Al-Si alloys has been carried out with variation of cooling rates in ingot casting and horizontal continuous casting processes. The influence of cooling rate on microstructure of ingot casting Al-Si alloy was investigated. The effect of forced cooling device and addition of raw metal with superdispersed microstructure was evaluated on the view point of the size controlling of primary silicon and eutectic silicon in Al-Si alloys during horizontal continuous casting process. The influence of heat treatment on tensile properties was also carried out.

Keywords: *Al-Si alloys, cooling rate, microstructure, mechanical properties, horizontal continuous casting*

1. Introduction

Al–Si alloys are used extensively in aerospace structural application and automobile industry because of excellent abrasion resistance, low coefficient of thermal expansion, and high strength-to-weight ratio. Eutectic or near-eutectic Al–Si alloys provide the best overall balance of properties which are referred to as 'piston alloys'[1].

Mechanical properties and casting quality of Al–Si alloys strongly depend on the size and the morphology of silicon crystals, secondary dendrite arm spacing (SDAS) and also the number of defects[2-4]. The morphology of Si phase during solidification may be sensitive to cooling/growth rate and to certain specific impurity additions[5-7]. Modification of the Al–Si alloys can be achieved in two different ways: by addition of certain elements (chemical modification) or with a rapid cooling rate (quench modification). In this study, Al-Si alloys were prepared in two casting processes: ingot casting with different thickness step block and horizontal continuous casting. The microstructure and mechanical properties of Al-Si alloys in different cooling rate were also investigated.

2. Experimental

The alloys for ingot casting are AP2 alloy and A390 alloy. Table 1 is the chemical composition of those two alloys. The base alloy was melted at a temperature of 800℃ in a graphite crucible. After degassed by Ar gas, the melt was poured into a steel mould. The mould is designed for four different thickness step block, which is 40mm, 20mm, 10mm and 4mm, respectively. The casting temperature is 695℃ for AP2 alloy and 780 ℃ for A390 alloy, which corresponds to the Al-Si phase diagram. Different thicknesses were designed to obtain different cooling rates. After the calculation of computer, the cooling rates were estimated to be 11.6℃/s (4mm thickness), 9.2℃/s (10mm thickness), 5.7℃/s (20mm thickness) and 3.3℃/s (40mm thickness), respectively.

Eutectic and hypereutectic binary Al-Si alloys were used in horizontal continuous casting(HCC). The materials of Al-18%Si alloy and Al-12%Si alloy were processed by HCC equipment. The horizontal continuous casting was performed at the temperature range of 690-720℃.

Table 1 Chemical composition of AP2 and A390 alloy (wt. %)

Alloy	Si	Cu	Mg	Fe	Al
A390	17.1	4.8	0.6	0.2	Bal.
AP2	11.2	4.2	0.6	0.2	Bal.

3. Results and discussion

3.1 Ingot casting of Al-Si alloy

Fig. 1 is the microstructure of AP2 alloy at different cooling rates. White dendritic one is α-Al and gray interconnected need-like one is eutectic silicon. As shown in these photos, both α-Al and eutectic silicon become to be finer with increasing cooling rate. Secondary dendrite arm spacing (SDAS) of α-Al changes from 40μm to 10 μm. This is coincidence with the following formula

$$d = 13840 v_L^2 - 7562 v_L + 1066 \tag{1}$$

where d is SDAS of α-Al and v_L local solidification rate[8]. The morphology of eutectic silicon does not change, which is still need-like. But it becomes to be much finer as short rod-like form with a rapid solidification.

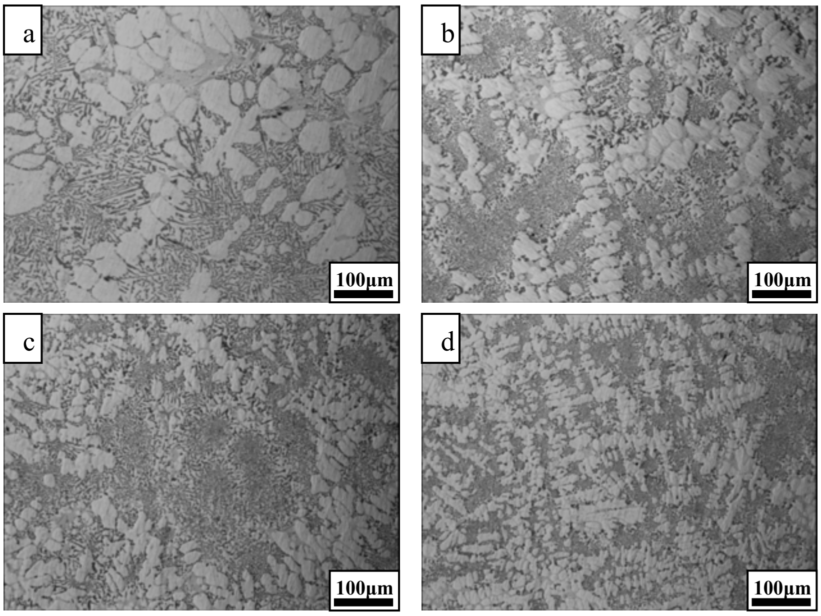

Fig. 1 Microstructure of AP2 alloy by ingot casting
(a) 40mm (b)20mm (c) 10mm (d) 4mm

Microstructure of A390 alloy is shown in Fig. 2. A series of morphologies of primary silicon were observed in A390 alloy: plate-shaped crystal of hexagonal form, octahedral equi-axed crystals, star-like crystals containing two to five radiating twin planes, and more or less spherical shapes, etc. The mean size of primary silicon decreases from 40 μm to 20 μm as the cooling rate increases. Interior microstructure of eutectic cell also becomes to be much finer in a rapid cooling rate. The morphology of eutectic silicon changes from coarse need-like shape to fine rod-like form and the SDAS of α-Al becomes to be much smaller. The tendency is as same as the one in AP2 alloy.

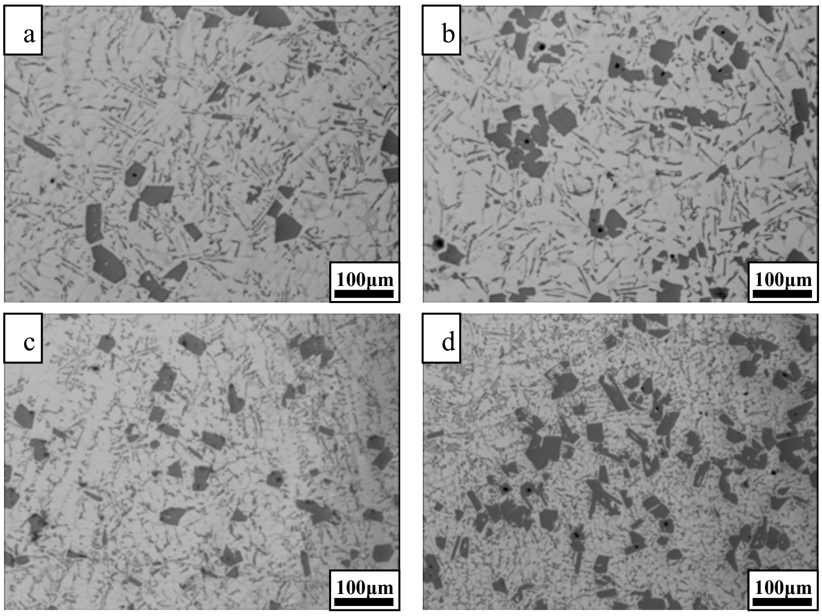

Fig. 2 Microstructure of A390 alloy by ingot casting
(a) 40mm (b)20mm (c) 10mm (d) 4mm

Higher cooling rate provides a bigger undercooling, which makes the critical radius of nucleus smaller. This means it is easier to form more nuclei. On the other hand, there is no enough time for grains to grow into coarse forms. Both of these two aspects are attributed to the resultant finer microstructure at a higher cooling rate.

3.2 Horizontal continuous casting of Al-Si alloy

3.2.1 Al-12%Si alloy

The casting of aluminum alloys for extrusion billets and rolling slabs has principally been carried out by the semi-continuous casting process (direct chill casting process). Horizontal continuous casting has many advantages such as lower investment cost, higher flexibility, longer casting times and so on. However, casting defects such as microsegregation and porosity are usually present in the as-cast microstructure which can lead to the deterioration of mechanical properties.The center of the cast bars was chosen to compare because it is the most frailty part in horizontal continuous casting alloy. The following pictures are chosen as the same position.

There are two cooling system in horizontal continuous casting: single and double cooling. Alloys processed by single cooling solidified in the air after drawn from the crystallizer. So the cooling rate is not rapid enough to make fine materials. Direct water spray method is adopted in double cooling process to obtain a higer cooling rate. The water jet can be spayed from mould to chill the alloys drawn from the crystallizer which is known as indirect chill. The temperature of cooling water is about 20℃ and the water consumption is 5-15m^3/h. Fig. 3 is the SEM of the alloys processed by single and double cooling horizontal continuous casting process. (a) and (c) are the views of α-Al in low magnification while (b) and (d) are the pictures of eutectic silicon in larger magnification. Both α-Al and eutectic silicon become to be finer. Mean SDAS of α-Al changes from 100 μm to 30 μm. The eutectic silicon was modified from coarse needle-like one to fine fibrous form. Double cooling method makes cooling rate much more rapid, which results in bigger undercooling. This induces finer microstructure of alloys after secondary cooling.

Tensile properties of two different cooling conditions in Al-12% Si can be seen in Table 2. Both the yield strength and ultimate tensile strength increase obviously after direct water cooling, especially for the UTS, which increases by 90 MPa. By introducing cooling water, the heat can convect rapidly in the cross-section of the billet. So the higher cooling rate of melt results in a bigger undercooling. This induces finer structure and enhanced mechanical properties.

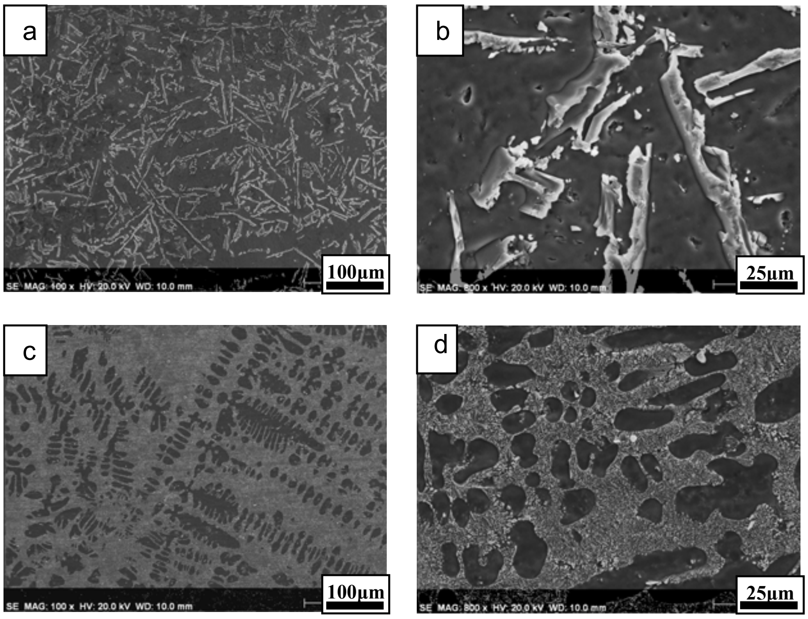

Fig. 3 Microstructure of Al-12%Si alloys at different cooling conditions

(a), (b) single cooling (c), (d) double cooling

Table 2 Tensile properties of Al-12Si alloy in different cooling conditions

Alloy	State	Yield strength（MPa）	UTS (MPa)	Elongation（%）
Single cooling	F	70	174	16.4
Double cooling	F	93	236	16.5

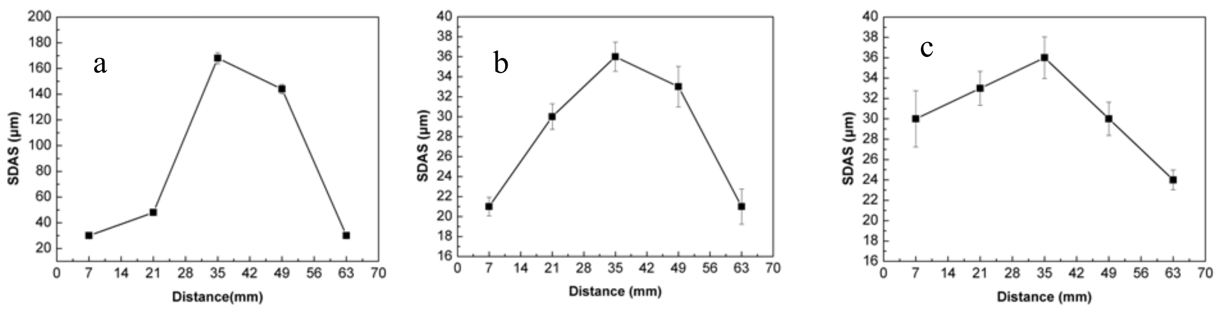

Fig.4 SDAS of the center of Al-12%Si alloys with different amount of raw metal

(a) 0% (b) 30% (c) 50%

Conventional modifiers are available to refine the primary or the eutectic silicon, but it is inevitable to increase the amount of impurity. Rapid cooling is another method to modify Al-Si alloy besides the elements such as Sr. This raw metal with superdispersed microstructure was processed by rapid cooling rate, which the alloy has SDAS as 13μm. Fig.4 is the SDAS of alloys with different amount of raw metal. As the amount of raw metal increases, the SDAS becomes to be much smaller and the difference between the center and the surface becomes to be smaller, too. This means the microstructure becomes to be more uniform due to its role as a modifier. Both α-Al and eutectic silicon become to be finer after adding raw metal as shown in Fig.5. The alloy with 30% raw metal has no big difference with the one with 50% raw metal.

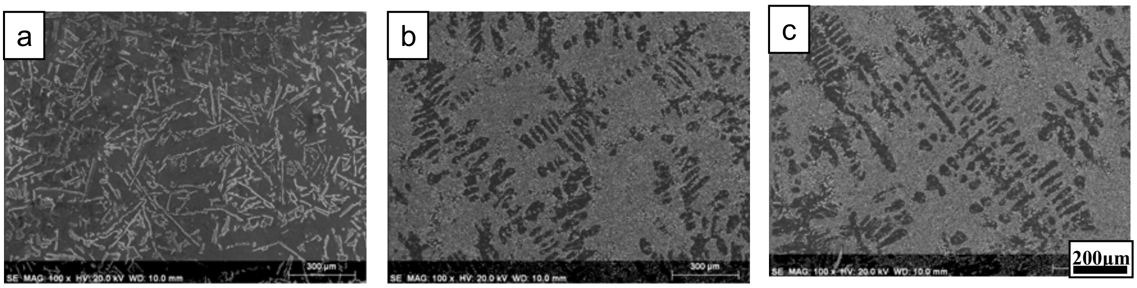

Fig.5 Microstructure of Al-12% Si alloys with different amount of raw metal
(a) 0% (b) 30% (c) 50%

The raw metal added for horizontal continuous casting process acts as modifier to refine the eutectic cluster. The modifier disperses uniformly in the alloy to form potential nucleus for solidification. It is easy to nucleate in a small undercooling. So when the surface starts to solidify, many nuclei come out to grow up before the solidification front. The solidification front moves quickly from the surface to the center for a medium diameter of billets (70mm). So the microstructure becomes to be uniform and fine in cross-section of the alloy. The addition of raw metal up to 50 percent does not help in further structural refinement. This is due to the fact that as the amount of inoculant particles participating in nucleation (at given undercooling) increases, so does the latent heat release leading to recalescence at a smaller undercooling, thereby lowering the efficiency of the grain refiner.

3.2.2 Al-18%Si

The usual method to refine primary silicon is to add the element P. But it is inevitable to introduce extra impurity. Rapid cooling is one of ways to modify Al-Si alloy to obtain fine microstructure. In this study, the size of primary silicon in raw metal processed by rapid cooling is about 20 μm. This alloy was put into the continuous casting alloy melt to act as modifier.As to heredity, silicon in rapid cooling ingot can keep small size during growth after remelting. These small silicon phase can be the nucleus in horizontal continuous casting Al-Si alloys. More nuclei mean more grains and finer structure. This can be proved in Fig. 6, the microstructure of alloys with adding raw metal. The average size of primary silicon decreases from 40 μm to about 30 μm after adding 15 percent raw metal. And the eutectic silicon also becomes to be finer. Increasing the content of raw metal to 30 percent, there is no big change in the microstructure for continuous casting..

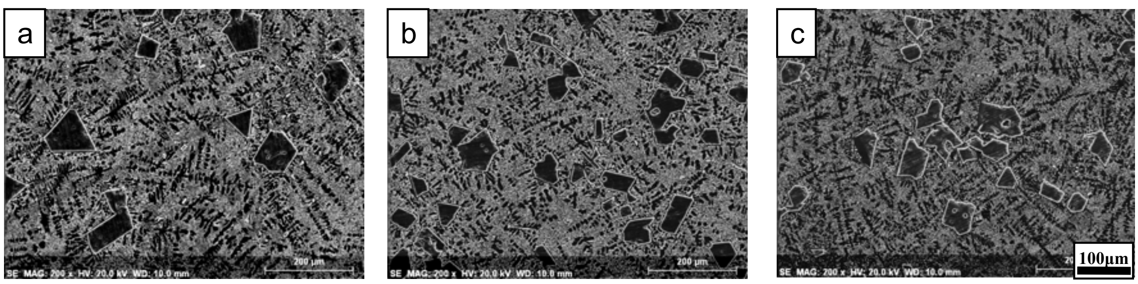

Fig. 6 Microstructure of Al-18%Si alloys with different amount of raw metal

(a)0%   (b) 15%   (c) 30%

The same situation was found for the results of mechanical properties, as shown in Fig. 7. The alloy with 15 percent raw metal has the best properties of strength . The melt containing 30 percent raw metal does not obtain further structural refinement. This is due to the fact that as the amount of inoculant particles participating in nucleation (at given undercooling) increase, so does the latent heat release leading to recalescence at a smaller undercooling, thereby lowering the efficiency of the grain refiner

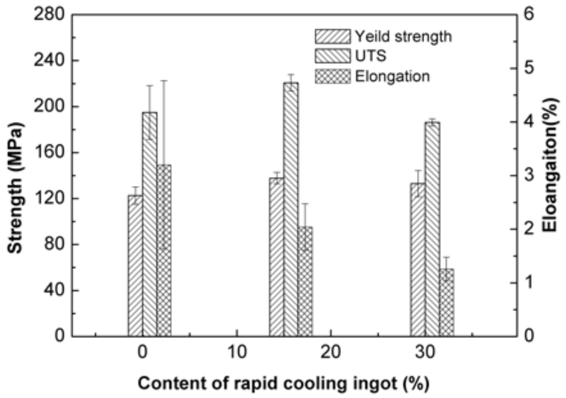

Fig. 7 Mechanical properties of Al-18%Si alloys with different amount of raw metal

4. Conclusions

From these observations, the following conclusions are drawn.

1. For ingot casting, the microstructure of AP2 alloy and A390 alloy becomes to be finer as the cooling rate increases.
2. Microstructure differs at different cooling conditions in horizontal continuous casting process. After double cooling, Al-12% Si alloys shows finer microstructure and better mechanical properties.
3. Raw metal with superdispersed microstructure processed by rapid cooling can modify both Al-12%Si alloy and Al-18%Si alloy. The optimum amount of raw metal is 30 percent for Al-12%Si and 15 percent for Al-18%Si alloy.

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