Research on Microstructure and Growth Mechanism of Different Primary Silicon in Hypereutectic Aluminum Alloy

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Abstract. The as-cast microstructure of a typical hypereutectic Al-25Si alloy was studied, and the growth mechanism of different primary silicon phases was analyzed. The results show that the as-cast microstructure phase composition of the alloy is mainly primary silicon and eutectic silicon. Primary silicon is mainly petal-like, massive and other complex polyhedrons, and there are a lot of cavities, cracks and other defects in the interior and boundary; Eutectic silicon is coarse and long needle-like, and the distribution is relatively messy, which seriously deteriorates the mechanical properties and cutting performance, and hinders the further application of the alloy in the field of lightweight pistons. Petal-shaped primary silicon is grown by combining five tetrahedral crystal nuclei in the melt into a decahedron, while bulk primary silicon is mainly caused by the unbalanced aggregation of impurity elements. And these two types of silicon phase growth methods are related to the twin groove growth mechanism, which is the result of a combination of multiple mechanisms.

Keywords: Hypereutectic, Al-Si Alloy, Microstructure, Properties, Primary Silicon, Twin Grooves, Growth Mechanism.

1. Introduction
Looking at the current research status of piston materials for vehicles and ships in various countries around the world, the key direction is lightweight pistons. With the advancement of high-power and supercharged internal combustion engines, the application of hypereutectic high-silicon aluminum alloys with higher silicon content in this field will receive more and more attention and attention from researchers [1-3].

The silicon content of hypereutectic aluminum silicon alloy is usually as high as 17%~26%. Compared with hypereutectic and eutectic Al-Si alloys with lower silicon content, there is a large amount of over-solid solution silicon in the matrix in the form of primary and eutectic silicon [4-5]. It can greatly reduce the density and thermal expansion coefficient of the alloy, reduce the cost of castings, and improve its volume stability and casting performance [6]. And with the increase of silicon content, these advantages can be further exerted. However, as the silicon content increases, the primary and eutectic silicon phases in the microstructure become more coarse and messy, making it more difficult to refine and deteriorate. The damage to the mechanical properties of materials has become more and more serious, especially the deterioration of their strength, plasticity and wear resistance [7]. Compared with...
Al-Si alloys with lower silicon content, the refinement and modification technology for such alloys with high silicon content at home and abroad is not mature enough, which limits its wide application.

In view of this, this article selects Al-25Si alloy, a typical representative of hypereutectic high-silicon aluminum alloy, as the object for research, and through analysis, grasps the formation mechanism of coarse phases, and provides theoretical basis for scientific researchers to make targeted modification, refinement, and strengthening.

2. Test Materials and Methods
The hypereutectic aluminum alloy selected in this experiment is Al-25Si alloy, which is prepared by adding silicon to pure aluminum. For high-silicon aluminum alloys, too high a pouring temperature will easily cause coarsening of the alloy microstructure and aggravate the getter oxidation of the alloy melt; If it is too low, it will cause poor fluidity of the molten metal and difficulty in forming, which is not conducive to the floating of slag inclusions and reduces the internal and surface quality of the ingot. Therefore, when choosing the pouring temperature, the pouring temperature should be appropriately lowered to make it as close to the liquidus line as possible under the premise of ensuring the fluidity of the molten metal, and the best microstructure refinement effect will be obtained. It can be seen from Figure 1 that when the silicon content is 25wt.%, the corresponding liquidus temperature of the Al-Si alloy is about 760°C. Usually the pouring temperature should be 10~50°C above the liquidus line. Based on experience, this experiment selects 770°C as the pouring temperature of the alloy.

The specific method is as follows: Under laboratory conditions, an improved low-temperature silicon addition method is adopted, and a bell jar is used to add bulk silicon to the pure aluminum melt. After it is completely melted, the temperature is raised to 770°C, poured into a rod-shaped mold, and samples are prepared after cooling. The microstructure and the cause of the coarse primary silicon phase are studied by means of analysis and detection methods such as scanning electron microscopy and optical metallurgical microscope.

3. Test results and Analysis

3.1 Microstructure Analysis of Hypereutectic Aluminum Alloy
Figure 2 is the microstructure of the Al-25Si alloy prepared in this experiment. It can be seen from the figure that the hypereutectic high-silicon aluminum alloy has the same phase composition as a generally prepared hypereutectic Al-Si alloy with a lower silicon content, such as A390 alloy). Both are composed of primary crystal silicon/eutectic silicon and α-Al, but the average size is larger. It can be seen that the morphology of primary silicon is more complex, mainly petal-like, block-like and other complex polyhedrons, irregular in shape and unevenly distributed, with many sharp edges, and the size is about...
20μm to 400μm. In addition, the eutectic silicon in the alloy microstructure is coarse and long needle-like, and the distribution is relatively messy; the α-Al matrix microstructure is also coarse, embedded in the silicon phase gap.

Figure 2. The as-cast microstructure of Al-25Si alloy (a) Low power morphology  (b) Petal-shaped primary silicon  (c) Polyhedral primary silicon  (d) Eutectic silicon

Further analysis found that there are a large number of defects such as cavities and cracks in the interior and boundary of the primary crystal silicon. Figure 3 shows the defect morphology of the interior and boundary of the Al-25Si alloy primary silicon. The above-mentioned microstructure and morphology will have obvious effect on the fracture of the alloy matrix, which will seriously damage the microstructure and mechanical properties of the alloy. As a result, the microstructure of each area is extremely uneven, the hardness is very different, the cutting performance is deteriorated, and the brittle fracture is easy to be directly applied to the workpiece processing.

Figure 3. The microstructure of defects of Internal and boundary of primary Si in Al-25Si alloy  (a) Low-magnification form 150×  (b) High-magnification form 300×
3.2 Growth Mechanism of Primary Silicon in Hypereutectic Aluminum Alloy

Jackson et al. once proposed the microstructure theory of the crystal interface. During the solidification of the alloy, the microstructure of the liquid and solid interface can be divided into two types from the atomic scale: rough interface and flat interface. When the free energy of the interface is the lowest, the interface is in a balanced microstructure. If solid atoms are randomly added to the interface, the interface will be roughened. At this time, the relative change in the free energy of the interface can be expressed by the following formula:

$$\Delta G_s = \Delta x (1 - x) + \alpha x L_n x + L_n (1 - x)$$  \hspace{1cm} (1)$$

The left side of the formula (1) is the relative change of the interface free energy, the interface free energy is $\Delta G_s$, the temperature at equilibrium crystallization is represented by $T_m$, and the total amount of all positions that atoms may occupy is represented by $N$. The percentage occupied after being occupied is represented by $x$, and $\alpha$ is the Jackson constant. $\alpha$ is different. From the relationship between $\Delta G_s / (NKT_m)$ and $x$, a curve can be obtained. On this curve, $\alpha$ is above 3. At the same time, when $x$ is less than 0.25 or greater than 0.75, $\Delta G_s / (NKT_m)$ is less than zero. At this time, the crystal interface is flat, and the flatness of the interface increases with the increase of $\alpha$. The microstructure of silicon crystal is diamond cubic, and this special microstructure leads to anisotropic crystal growth. The Jackson factor $\alpha$ of the silicon crystal interface is above 5, so the interface will be relatively smooth during growth [8].

There are three growth mechanisms for primary silicon: the twin groove mechanism, the two-dimensional nucleation mechanism, and the step growth mechanism caused by crystal imperfections. The growth and nucleation of primary silicon is not only one of them, not unique, but each primary silicon particle is based on the dynamic environment it is in to produce a growth mechanism consistent with it. This mechanism is closely related to the dynamic environment. It is precisely because of the vast difference in dynamic environment that the shape, quantity, size, and distribution of primary silicon are different, and there are many morphological characteristics such as petals and blocks.

Petal-like primary silicon is often found in hypereutectic Al-Si alloys with higher silicon content, as shown in Figure 4(a). The angle between every two adjacent branches in the five branches is about 70.5 °C to 75°C, and there are usually twin grooves in the front part of the branch. Kobayashi et al. believe that this petal-shaped primary silicon crystal nucleus is formed by combining five tetrahedral crystal nuclei in the melt into a decahedron and then growing [9]. There is a five-fold twinning relationship between the five branches. During the solidification process, the five branches with a higher crystal face index will accelerate their growth due to the non-faceted growth characteristics of primary silicon. It eventually grows into a five-petaled petal shape.

![Figure 4](image-url)

**Figure 4.** A schematic illustrating the growth sequences of two kinds of primary Si in Al-25Si alloy

(a) Petal-shaped primary silicon   (b) Polygonal bulk primary silicon
There are many opinions about the growth mechanism of bulk primary silicon. The earlier one was the growth mechanism of twin grooves, namely TPRE (Twin Plane Re-entrant Edge). That is to say, the growth rate of slab-shaped primary silicon at the twin groove is faster than that of other parts such as the twin edge, which causes the edge to be elongated; The current consensus is that there are a large amount of impurity elements in the alloy melt, some of which are concentrated in the grooves of the primary silicon twins, and are not easy to diffuse to other parts. However, some are unconstrained and easily diffuse into the distant melt, which will cause an unbalanced accumulation of impurity elements near the grooves of the primary silicon twins, and the impurity elements at the grooves are significantly higher than other parts [10]. This squeezes out part of the silicon atoms, reduces the concentration of silicon atoms in the groove, and slows down the growth rate of the silicon phase in this part. But at the same time, the twin groove growth mechanism still exists, resulting in the growth rate of the groove part and the edge part is similar, and it grows into a polygonal block as shown in Figure 4(b).

Due to the uneven distribution of impurity elements and other factors, the silicon atom concentration is poor, and the growth of primary silicon in the heavily enriched part will slow down or even stop. In the subsequent solidification process, there are directional differences in the growth of primary silicon at the twin grooves, and the slow-growing parts solidify later. As a result, cavities as shown in Figures 2 and 3 will appear in the primary crystal silicon; after the alloy is solidified, the primary silicon grows into a coarse irregular shape with many sharp corners and uneven distribution. The stress generated during the casting stage is easily concentrated at the sharp corners and burrs on the edges of the cavities [11-12]. After the solidification is completed, the internal and boundary parts of the silicon phase are partially broken due to the inability to withstand greater stress, forming a large number of cracks, as shown in Figure 3(b). The existence of these defects will inevitably destroy the uniformity and integrity of the alloy, and seriously reduce the mechanical properties and cutting performance of the alloy.

4. Conclusion

(1) The phase composition of the as-cast microstructure of the hypereutectic Al-25Si alloy selected in the experiment is mainly primary silicon and eutectic silicon, and the Al-Si alloy with a lower average size of silicon content is much larger. Primary silicon mainly has petal-like, block-like and other complex polyhedral shapes, with irregular shapes and uneven distribution, and there are a large number of voids, cracks and other defects in the interior and boundary; Eutectic silicon is coarse and long needle-like, and the distribution is relatively messy; α-Al is also coarse and embedded in the silicon phase gap. The above-mentioned morphology has a very obvious splitting effect on the alloy matrix, which will seriously damage the mechanical properties and cutting performance of the alloy.

(2) There are three growth mechanisms for primary silicon: the twin recessed angle mechanism, the two-dimensional nucleation mechanism, and the step growth mechanism caused by crystal imperfections. Petal-like primary silicon is formed by combining five tetrahedral crystal nuclei in the melt into a decahedron and then growing. The growth mechanism of bulk primary silicon is mainly caused by the unbalanced aggregation of impurity elements. And these two types of silicon phase growth methods are related to the twin groove growth mechanism, which is the result of a combination of multiple mechanisms.

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