Effect of Mg on Microstructure and Mechanical Properties of Hypereutectic Al-25Si Alloy

Gaozhan Zhao *, Wen Chen, Shuxin Chai, Ming Li, Jianquan Tao and Shiqing Gao

No.59 Institute of China Ordnance Industry, 400039 Chongqing, China

*Corresponding author e-mail: chfzgz@126.com

Abstract. The effects of Mg Addition mode and amount on the microstructure and mechanical properties of hypereutectic Al-25Si alloy after modification were analyzed. The results show that the Mg2Si phase is relatively small, which is in the shape of granular or small bone, and has relatively little damage to the tissue; The hardness of the alloy is directly proportional to the amount of Mg added. When 1.5wt. % Mg is added, the microstructure and properties reach the best state. If the amount of Mg 2Si is excessive, it will gradually change into a coarse mesh, Chinese character shape and deteriorate the properties. The main reason is that there is a close adhesion growth relationship between Mg2Si and eutectic silicon. The modification and refinement lead to the lack of nucleation basement and the inhibition of growth of Mg2Si. At the same time, the modified residual AlP phase is used as the nucleation point. Mg2Si phase did not coarsen obviously, and other phases also maintained in a good shape.

Keywords: Hypereutectic, Al-25Si Alloy, Mg, Mg2Si Phase, Eutectic Silicon, Microstructure, Properties

1 Introduction

Due to the large amount of super soluble silicon in the matrix, hypereutectic Al-Si alloy can greatly reduce the density and thermal expansion coefficient of the alloy, reduce the manufacturing cost, and improve the volume stability and process performance of the casting [1-3]. With the development of high-power and light-weight supercharged internal combustion engine, modern industry has higher and higher requirements for engine performance. The traditional hypereutectic aluminum silicon alloy cannot meet the development needs of the equipment. The hypereutectic aluminum silicon alloy with higher silicon content (silicon content up to 17% ~ 26%) is attracting more and more attention of researchers due to its outstanding advantages, and its application also shows a significant growth trend.

This kind of hypereutectic Al-Si alloy can reduce the specific gravity of the alloy, decrease the coefficient of linear expansion, improve the thermal conductivity, wear resistance and volume stability, and significantly reduce the piston density and reciprocating inertia force. When working, the surface temperature of the piston is low, and the carbon on the top is less, so it becomes an ideal piston material.
The hypereutectic Al-Si alloy with Si content in the range of 17% ~ 26% can be divided into the following three groups according to Si content: Si content in group A is 17% ~ 19%, Si content in group B is 19% ~ 22%, and Si content in group C is 22% ~ 26%. A, Group B and group C are relatively mature in research and application due to their better processability, and have more practical production and application. Group C has lower coefficient of linear expansion, better wear and corrosion resistance, and better service performance than the former two groups, which is more suitable for the operation of high-speed engine piston. However, due to the high content of Si, the primary and eutectic silicon phases in the fabric are abnormally coarse and difficult to modify and strengthen. In recent years, strengthening the matrix on the basis of modification and refinement to improve the crack resistance of the piston has become a research hotspot and the main research direction of this experiment [4-5].

2 Test materials and Methods
In this experiment, the cast Al-Si alloy is hypereutectic Al-25Si alloy with Si content of 25%. The modifier is Al-1.2P-5Cu intermediate alloy, and the strengthening element is pure Mg. In the experiment, a new type of Al-1.2P-5Cu master alloy was prepared by vacuum induction melting, and a certain amount of Mg was added into hypereutectic Al-25Si melt under certain technological conditions, then the alloy was poured into square sample and cooled, and then T6 state heat treatment was carried out. Finally, the microstructure of Al-25Si alloy was analyzed by different test methods, and the mechanism of modification and performance improvement was further studied through various performance test experiments and comparative experiments. The heat treatment process is 510 °C × 6h solid solution + 50 ~ 80 °C water quenching + 210 °C × 10h aging, followed by furnace air cooling, the quenching transfer time is not more than 6S. The SX2-10-13 type heat treatment furnace is selected, the microstructure is analyzed by metallographic microscope, and hb-3000a type hardness tester is used for hardness measurement. The sample size of Al-25Si alloy is shown in Fig. 1.

![Fig. 1 Sample size of Al-25Si alloy](image)

3 Test results and Analysis

3.1 Effect of Mg Addition on the Microstructure of the Alloy
For the addition temperature and holding time of Mg in Al-Si alloy, the requirements are relatively simple, that is to ensure that Mg can be fully melted in the alloy melt to achieve the best solution effect and prevent burning loss. Therefore, the temperature should not be too low or too high. According to the melting point of Mg (650 °C), combined with the conditions of adding mg after modification and pouring temperature (770 °C), and because the later adding Mg, the less the burning loss, the temperature of adding Mg is 770 °C before pouring and the holding time is 1-2 minutes, which can ensure the maximum solid solution of Mg in the matrix and minimize the burning loss.

In general, the addition of Mg element to hypereutectic Al-Si alloy is prior to the modification and refinement. At this time, the silicon phase is relatively large, and after the addition, the coarse Chinese character or network Mg3Si phase is often formed, which increases the workload and difficulty of modification and refinement. For example, the commonly used Al-Si-Mg alloy, the process used in this experiment is adding the intermediate alloy modified silicon phase first and then adding magnesium. Fig. 2 shows the microstructure of as cast alloy after adding 1.5wt.% Mg before and after modification.
Fig. 2 Comparison of as cast microstructure before and after modification by adding 1.5wt. % Mg
(a) First add Mg, then metamorphism; (b) First metamorphism, then add Mg

Before modification, Mg is added when the melt temperature rises to 770 °C, and continues to rise after stirring; after modification, Mg is added when the melt temperature drops to 770 °C, and refined after holding for 2 minutes. Obviously, the addition of Mg2Si before metamorphism is unusually thick, which is a typical Chinese character or network, while the addition after metamorphism is much smaller, which is in the shape of granule or small bone, which has relatively little damage to the tissue and is relatively easy to make further improvement.

Fig. 3 is SEM and EDS analysis of Mg2Si phase (dark granular or bony) in as cast alloy structure after adding 1.5wt. % Mg after modification.

![Fig. 3](image)

**Table 1**

| Element | weight%  | atomic% |
|---------|----------|---------|
| Al      | 54.93    | 52.59   |
| Si      | 18.73    | 17.53   |
| Mg      | 26.34    | 29.88   |

3.2 Effect of Mg Addition on Microstructure and Properties of the Alloy

It is very important to determine the amount of Mg Addition for the alloying effect of Mg. Fig. 4 shows the relationship curve between the amount of Mg Addition and the hardness of Al-25Si alloy. It can be seen that in a certain range, the larger the amount of Mg addition, the stronger the solution strengthening effect, and the more fully the strengthening effect of Mg can be exerted.
Fig. 4 Effect of Mg Addition on the hardness of modified Al-25Si alloy

Although it has been determined that the addition sequence of Mg is after the modification treatment, which can make the Mg$_2$Si phase relatively small, but with the large amount of Mg added, the Mg$_2$Si phase in the structure will be gradually coarse, to a certain extent, it will still exist in the form of Chinese characters or network, and the cleavage effect on the matrix will be more and more large, and the comprehensive properties of the alloy will not increase but decrease. Therefore, the principle of adding Mg to the alloy in this experiment is that the hardness should be as high as possible on the premise of ensuring that the phases in the structure are not coarsened. Since Fig. 4 has shown that the hardness increases with the increase of Mg addition, we only need to ensure that the structure is not significantly coarsened.

Fig. 5 is the change diagram of the as cast microstructure of Al-25Si alloy after adding different Mg content. Obviously, when 1.5wt. % Mg is added, the Mg$_2$Si phase is not obviously coarsened, and other phases also maintain the optimal shape. When excessive addition (as shown in Fig. 5 (e) and (f)), the reticular and Chinese character shape Mg$_2$Si gradually becomes obvious, and the shape of other phases in the tissue also changes greatly. In conclusion, when the Mg content of this experiment is 1.5wt%, it is beneficial to maximize the performance.

Fig. 5 Effect of Mg Addition on Microstructure of modified Al-25Si alloy

(a) 0.5wt.%  (b) 1wt.%  (c) 1.5wt.%  (d) 2wt.%  (e) 3 wt.%  (f) 4wt.%

Fig. 6 is the XRD analysis of the as cast alloy 3 (as shown in Fig. 5 (c)) obtained from the original as cast alloy 1 $\times$ 2 $\times$ 4 wt.% as cast alloy 2 $\times$ 4 wt.% as cast alloy, 4 wt.% as cast alloy 3 $\times$ 1 wt.% Mg.
(as shown in Fig. 5 (c)). It is obvious that Mg$_2$Si phase is added to the matrix, and the low peak area of the 3 × curve of the alloy fluctuates greatly. It is inferred that there may be more new phases. However, because the content of Cu, P and other elements in the alloy is very small, the wave peak is low, which cannot be determined here.

![XRD patterns of alloys 1#, 2#, and 3#](image)

**Fig. 6** Comparsion about XRD patterns of alloys 1#, 2#, and 3#

### 3.3 Discussion

The main purpose of adding Mg in this experiment is to improve the strength, hardness and wear resistance of Al-Si alloy by using the solution strengthening produced in the matrix and the precipitation strengthening brought by the reaction of Mg$_2$Si phase with Si element in the matrix. Therefore, the more added mg before the non-coarsening of the structure, the more favorable.

The size of Mg$_2$Si phase after metamorphism is much smaller than that before metamorphism. The main reasons are as follows. First of all, there is a close adhesion growth relationship between Mg$_2$Si phase and eutectic silicon. Although there are differences in their spatial groups (fm3m for Mg$_2$Si phase and fd3m for eutectic silicon), they are all face centered cubic lattice, and the side of the first eutectic silicon wafer is {111} low energy surface [6]. Therefore, in the process of crystallization, Mg$_2$Si phase can nucleate and grow on the side of eutectic silicon wafer as the substrate. However, in the refined Al-Si alloy, the eutectic silicon has been transformed into fiber like or short rod-shaped. The side of this shape not only contains {111} low energy surface, but also is composed of a variety of complex orientation planes. The surface is distributed with a large number of stacking faults and crystal twins [7], with a high density. Therefore, it is no longer necessary to provide a base for the nucleation of Mg$_2$Si phase, resulting in the difficulty of nucleation and the inhibition of growth. Secondly, when the intermediate alloy modifies the silicon phase, some AlP phases remain, and their dispersion in the melt can also be used as the nucleation point of Mg$_2$Si phase, so that it can be granulated to a certain extent [8-10], and finally grow into granular or small skeletal (as shown in Fig. 5 (c)). Because of the above reasons, the amount of Mg added in this experiment can break the limit of 0.4 ~ 0.7wt. % and reach 1.5wt. % [11], so that the strengthening effect of Mg can be brought into full play.

### 4 Conclusions

1) After modification of silicon phase and addition of magnesium, the Mg$_2$Si phase is relatively small, in the shape of granular or small bone, and has relatively little damage to tissue.

2) The hardness of the alloy is in direct proportion to the amount of Mg added. When 1.5wt. % Mg is added, the microstructure and properties reach the best state. If the amount of Mg 2Si is excessive, it
will gradually change into a coarse mesh and Chinese character shape, which will deteriorate the properties.

3) There is a close adhesion growth relationship between Mg$_2$Si and eutectic silicon. The modification and refinement of silicon phase will lead to the lack of nucleation substrate and the inhibition of growth of Mg$_2$Si. At the same time, the modified remaining AlP phase is used as the nucleation point, resulting in the refinement of structure and the improvement of performance.

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