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ORIGINAL ARTICLE

The Improvement in Mechanical Properties and Strengthening Mechanism of The New Type of Cast Aluminum Alloy with Low Silicon Content for Automotive Purposes

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Abstract The effects of different Si and Cr contents on the microstructure and mechanical properties of new type aluminum alloy with low silicon content were studied by means of hardness test, tensile test and metallographic preparation, SEM, EDS and DSC. The results showed that when the Si content increased gradually, the hardness and tensile strength increased first and then decreased. When the Si content was 3.5%, the hardness and tensile strength reached the maximum. The microstructure observation showed that when the Si content was 3.5%, the microstructure was the most fine and dense, and the secondary dendrite arm spacing (SDAS) of the alloy had the minimum value. When the content of Cr element increased gradually, the tensile strength and elongation showed a trend of increasing gradually, and the maximum value was obtained at 0.5%. When Si was 3.5% and Cr was 0.5%, the best mechanical properties were obtained. At this time, the microstructure of the alloy was fine, dense and uniform, and Mg2Si strengthening phase was precipitated during heat treatment. Cr element has the functions of solid solution, fine crystal and dispersion strengthening. Therefore, the tensile strength, yield strength and elongation of the new aluminum alloy were 350.7 MPa, 303.0 MPa and 8.56%, which has obvious advantages over the traditional cast Al-Si alloy.

Keywords Al-Si aluminum alloys · Strengthening phase · Microstructural evolution · Tensile property · Fracture appearance

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1 Introduction

With the advancement of science and technology and the development of industrial production, cast aluminum alloy has obvious advantages of light weight. It is widely used in the fields of automobile, aviation industry, machinery manufacturing, etc.[1]. Al-Si cast aluminum alloy has excellent casting performance, good corrosion resistance, ductility, plasticity, high strength-to-weight ratio and low cost of casting manufacturing. Therefore, the main research direction is to obtain aluminum alloy with better properties [2, 3]. Replacing the traditional steel structure with an aluminum alloy structure can reduce the weight of the vehicle by 30% to 40%, reduce the weight of manufacturing engines by 30% and reduce the weight of manufacturing wheels by 50% [4]. The A356 cast aluminum alloy is a typical Al–Si–Mg ternary alloy, which has good fluidity, no hot cracking tendency, small linear shrinkage. The A356 cast aluminum alloy has small specific gravity, good corrosion resistance and small degree of strength reduction with casting wall thickness. Thin-walled and complex-shaped castings can be cast due to these advantages, and the castings can achieve good mechanical properties by heat treatment. This kind of cast aluminum alloy is mainly used for automobile and motorcycle wheels [5].

Generally, the mechanical properties of cast aluminum alloys are related to the casting process and heat treatment process and also closely related to its chemical composition. The mechanical properties change with the ratio of Si and Mg [6]. The change of composition of cast aluminum alloy has a great influence on its alloy properties. For example, the addition of Cr can improve the elongation and stress corrosion resistance of aluminum alloy. With the development of automobile lightweight and the higher performance requirements of various aluminum alloy parts, it is necessary to develop and study an aluminum alloy with better comprehensive performance than A356 aluminum alloy. Therefore, taking A356 aluminum alloy as the research object, on the premise of constant magnesium content, the effects of different Si and Cr elements on the microstructure and mechanical properties of aluminum alloy were discussed. It is hoped that the mechanical properties of materials can be greatly improved under the premise of ensuring good comprehensive properties and basically not increasing the manufacturing cost. These tasks aim to make a reasonable explanation of the mechanism and lay a foundation for the lightweight of automotive aluminum alloy materials.

2 Experimental

First, the composition design of the new cast aluminum alloy was carried out. The ingredients were calculated according to the required composition. The A356 aluminum alloy was diluted with pure aluminum to get alloys with Si contents of 2.5, 3.0, 3.5, 4.0 and 4.5%. The chemical composition of A356 is given in Table 1. No Fe and Ti were added, and their contents were extremely small. The optimum content of Si element was determined by subsequent experiments. Subsequently, Al-10Cr master alloy was added to obtain Al–Si–Mg alloys with Cr contents of 0.1%, 0.3% and 0.5%. The other experimental conditions, such as heat treatment parameters, tensile test parameters and experimental environment temperature, were the same throughout the study. All material variants were solution heat treated for 2 h at 540 °C in a resistance furnace, quenched in water (with water temperature < 60 °C) and artificially aged at 170 °C for 8 h to a T6 temper.

The composition of the materials was analyzed using a spectrometer SPECTO MAXx. The tensile bar was processed from the ingot, and the dimensions of the tensile bar are given in Fig. 1. The tensile test was carried out on a MTS microcomputer-controlled universal testing machine. The hardness test was carried out on a MC010-HBS-3000 manual turret Brinell hardness tester. The sample size for the hardness test was Φ15mm*15 mm cylinders, both tensile test and hardness measurement results shown represent the average of three measurements. The processed cylindrical sample was ground and then polished, then etched with a 0.5% hydrofluoric acid solution, metallographic examinations performed with a Nikon Eclipse MA100 microscope. Image-Pro Plus (IPP) software is a tool for quantifying statistics in microanalysis. In order to study the relationship between Si contents and eutectic structure, the author used IPP (Image Pro Plus) software to quantify the area fraction of eutectic microstructure. The specific method was selecting three images that were magnified 200 times randomly for using the software to capture and calculate statistics. The tensile fracture morphology was observed using a HITACHI SU-1510 scanning electron microscope. A differential thermal analysis experiment was carried out on a DSC-Q2000. The sample size was 3 mm*3 mm*1.5 mm, and the surface oxide layer was sanded with sandpaper and weighed in a copper crucible, where the heating rate was 20 °C/min.

3 Results and Discussion

3.1 Thermodynamic Phase Diagram Calculation

Thermo-Calc software was used to calculate the phase diagram. The purpose was to analyze the change of phase and the volume fraction of the precipitated strengthening phase. The phase was changing when the Cr system was at 0 ~ 1%, Fig. 2. With the decreased of temperature, the liquid phase gradually transformed into the mixed crystal structure of α-Al phase and Mg_2Si when the Cr contents

Table 1 Chemical composition of A356 aluminum alloy wt(%)

Elements	Si	Mg	Cu	Mn	Fe	Zn	Ti	Al
Content	7.2	0.42	0.013	0.005	0.101	0.013	0.117	Balance

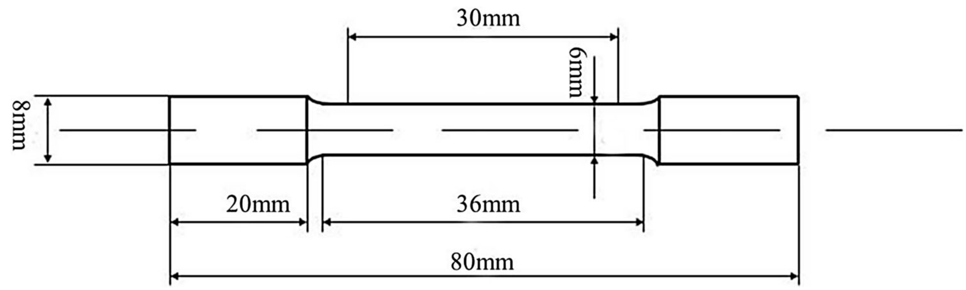


Fig. 1 Tensile sample drawing

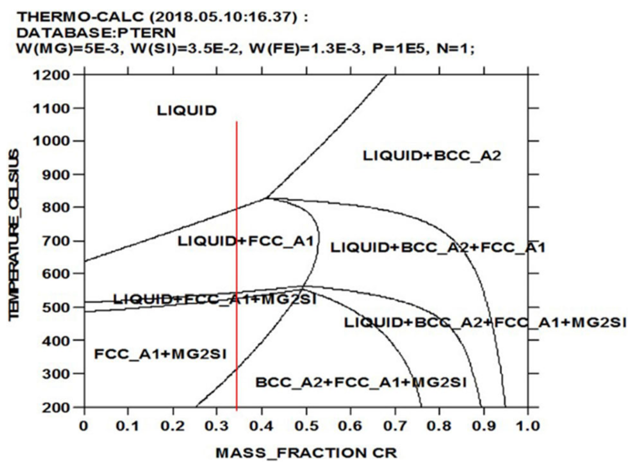


Fig. 2 Phase diagram of Cr contents change (3.5% Si)

were in the range of 0.3 $\sim$ 0.4%. Al is an FCC structure, and Al and Fe elements are mutually soluble to form a stable BCC. The simulation was carried out, respectively, in order to study the change of Mg_2Si phase fraction under the change of Si and Cr.

Figure 3 presents the comparison of Mg_2Si phase fraction at 2.5% and 3.5% Si. Curve 3 represents the change of Mg_2Si. It is not difficult to find that the ordinates of the two were basically the same. It indicated that the Mg_2Si formed by the combination of Mg and Si reached saturation. Because the mass ratio of Mg and Si is less than 1.73, Si is excessive [7]. The influence on the mechanical properties was theoretically analyzed after the experiment. Similarly, the results of the simulation calculation of Cr were compared and analyzed. The phase fraction of Mg_2Si was not changed by the addition of Cr.

3.2 Effects of Different Si Contents

In order to study the influence of Si contents on the microstructure and mechanical properties of five aluminum alloys, five component points were selected for experimentation with unchanged Mg contents. The specific component design scheme is given in Table 2. Experiment based on the contents of the table, the melted ingots were subjected to spectrometer test components and averaged.

3.2.1 Mechanical Properties

Brinell hardness tests on cylindrical samples and tensile tests on tensile test bars were carried out on samples with different Si-contents. Figure 4 revealed the change of Brinell hardness of samples with different Si contents. The line graph of tensile strength, yield strength, and elongation of samples with different Si contents was demonstrated, Fig. 5.

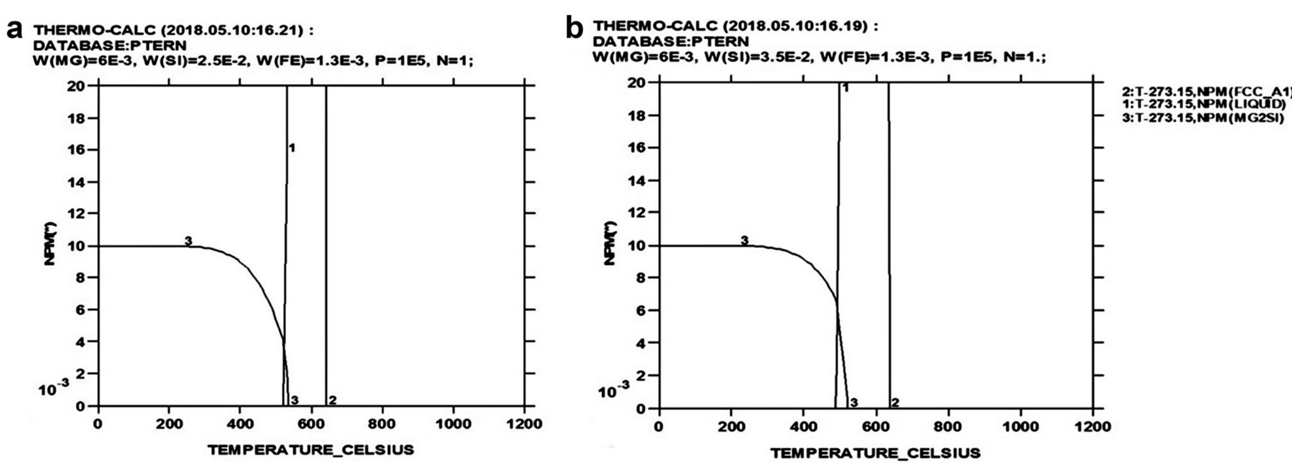


Fig. 3 Mg_2Si phase volume fraction with different Si contents **a** 2.5% Si; **b** 3.5% Si

Table 2 Number of samples with different Si contents

Batch	1	2	3	4	5
Silicon (%)	2.5	3.0	3.5	4.0	4.5

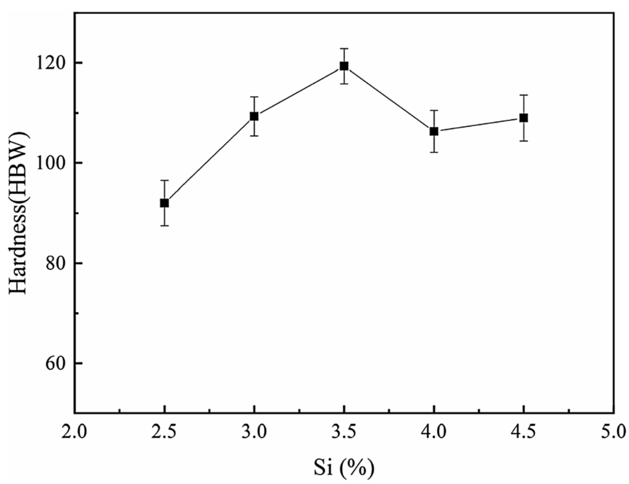


Fig. 4 Effect of Si contents on hardness

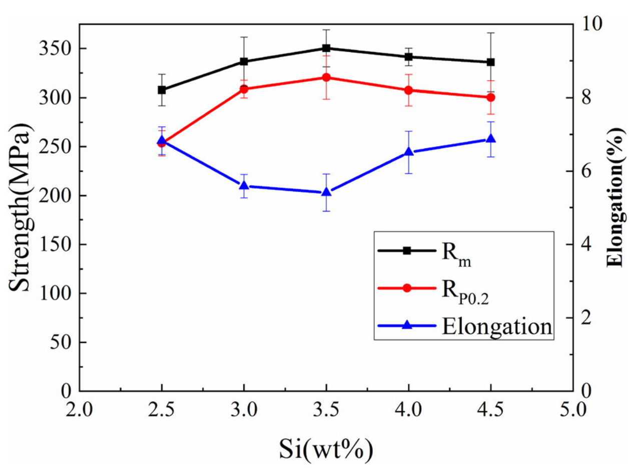


Fig. 5 Effect of Si contents on mechanical properties

It could be seen that the Brinell hardness value showed a significant upward trend and maintained a growth rate of more than 10% when the Si contents were increased from 2.5% to 3.5%. But when the Si content exceeded 3.5%, Brinell hardness value showed a downward trend, and the subsequent changes were less obvious, Fig. 4. This is consistent with the change of mechanical properties of aluminum alloy in T6 temper, Fig. 5. The tensile strength and yield strength were the lowest when Si content was 2.5%, but the elongation was higher. With the increase of Si content, the tensile strength gradually increased and then decreased. The strength reached the maximum when the Si content increased to 3.5%. The change trend of elongation was that, the elongation gradually decreased and then increased. The elongation reached the minimum value when the Si content was 3.5%. Since the change of Mg had a great influence on the elongation, it was considered to appropriately reduce the Magnesium content to ensure good plasticity. The results showed that the change of the ratio of Si and Mg had obvious influence on the mechanical properties of aluminum alloy, further increasing the mechanical properties by adding other trace elements. It could be explained that the Si content had a great influence on the hardness and mechanical properties of the aluminum alloy.

3.2.2 Microstructure

The observed micrographs are given in Fig. 6. After heat treated for 2 h at 540 °C, quenched in water (with water temperature < 60 °C) and aged at 170 °C for 8 h, the needle-like Al-Si eutectic phase transformed into granular and coralline shapes and distributed uniformly among dendrites. The second phase had certain dispersed and granulation compared with the as-cast alloy. The effect of the second phase on the alloy matrix was greatly weakened [8].

It could be seen that the content of the second phase based on Si increased with the addition of Si contents, so that the tensile strength and yield strength of the material got improved, Fig. 6. The statistics also showed that the content of aluminum–silicon eutectic structure also increased with the addition of Si contents, Fig. 7. This indicated that the concentration of Si reached the eutectic concentration around the α-Al matrix as the concentration of Si increased gradually, which in turn formed eutectic Si. It will hinder the growth of the primary α-Al phase and obtain a relatively fine alloy structure; fine and uniform particles contributed to the improvement in the mechanical properties of the alloy [9]. The metallographic structure was the smallest and intensive when the Si content was 3.5%, so the strength reached the maximum.

The performance of aluminum alloy castings is related to the secondary dendrite arm spacing (SDAS). The smaller the secondary dendrite arm spacing, the better the mechanical properties, which has been confirmed by many experimental data [10]. The secondary dendrite arm spacing had a certain change, and the statistical calculation was

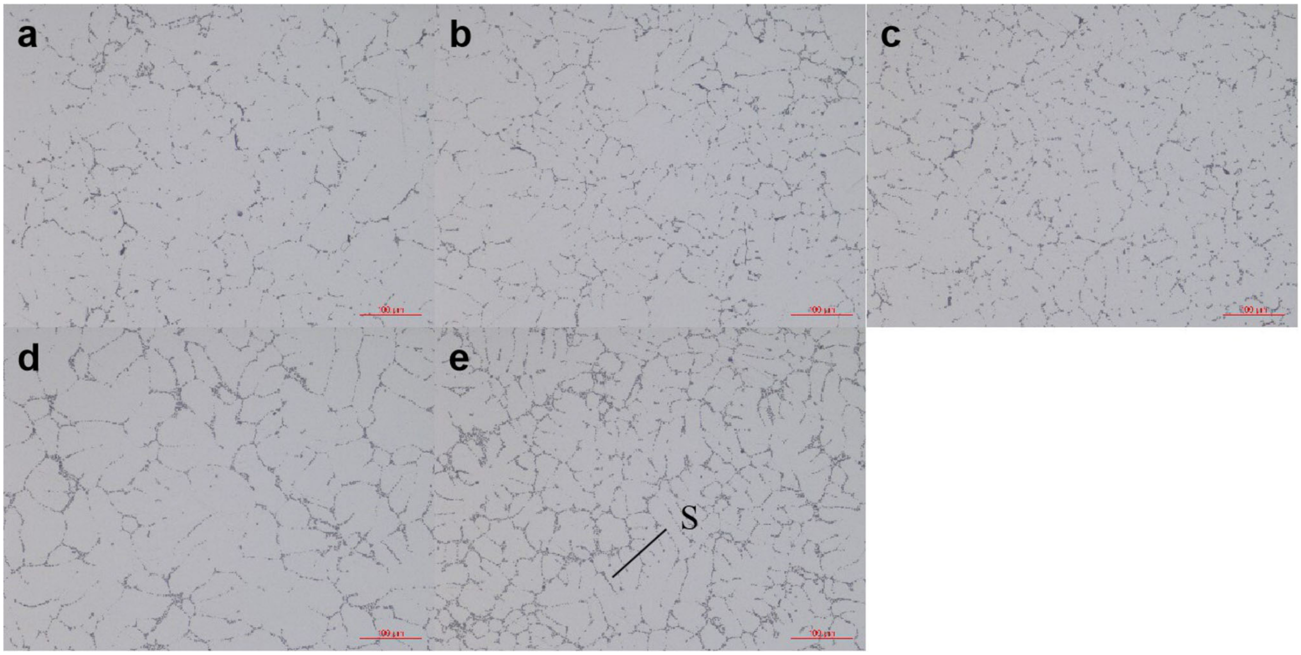


Fig. 6 Effect of Si contents on microstructure **a** 2.5%; **b** 3.0%; **c** 3.5%; **d** 4.0%; **e** 4.5%

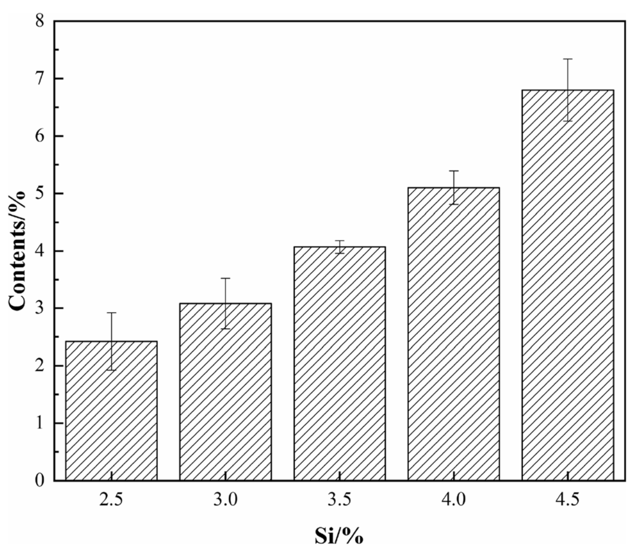


Fig. 7 Effect of Si on the contents of eutectic structure in Al–Si–Mg alloys

performed in multiple fields of view using IPP software and then averaged. The straight line at S represented the sum of multiple secondary dendrite arm spacing, Fig. 6e. The results calculated by this method were given (including Si and Cr elements), Fig. 8. The change of secondary dendrite arm spacing is determined by the nature of the alloy and the solidification speed. The solidification rate is controlled to be the same. The minimum secondary dendrite arm spacing of the alloy was 25.5 μm when the Si content was 3.5%. The corresponding strength of the alloy appeared to be the highest point, which indicated that the effect of the secondary dendrite arm spacing of the alloy on the strength was significant. As the Si content increased, the Mg_2Si content also increased, mostly in the solid solution form in the α-Al matrix, like the white particle in the red circle, Fig. 9a. The spectrum analysis of energy-dispersive spectrometer indicated the possibility of Mg2Si, Fig. 7b. After heat treated for 2 h at 540 °C, quenched in water (with water temperature < 60 °C) and aged at 170 °C for 8 h, Mg_2Si precipitates improved the strength and hardness of the material [11]. However, with the further increased of Si content, it was easy to form acicular or flaky Si. Due to the brittleness of the Si crystal, the mechanical properties of the material decreased as the content increased.

3.2.3 Tensile Fracture Morphology

The fracture surface of the tensile test was observed under scanning electron microscope. The sample was plastically deformed because of the shear stress, resulting in different degrees of necking. The section was grayish and lacked metallic luster, indicating that the sample had good plasticity. The tensile fracture morphology of the T6 alloy was given. It could be seen that the tensile fracture of the alloy showed a distinct dimple-like structure, showing typical ductile fracture characteristics. It indicated that it had good toughness and ductility. From the comparison of the fracture morphology, it could be seen that the difference was not obvious when the Si content was 3.0, 3.5 and 4.0%, just the number of dimples and the uniformity of distribution

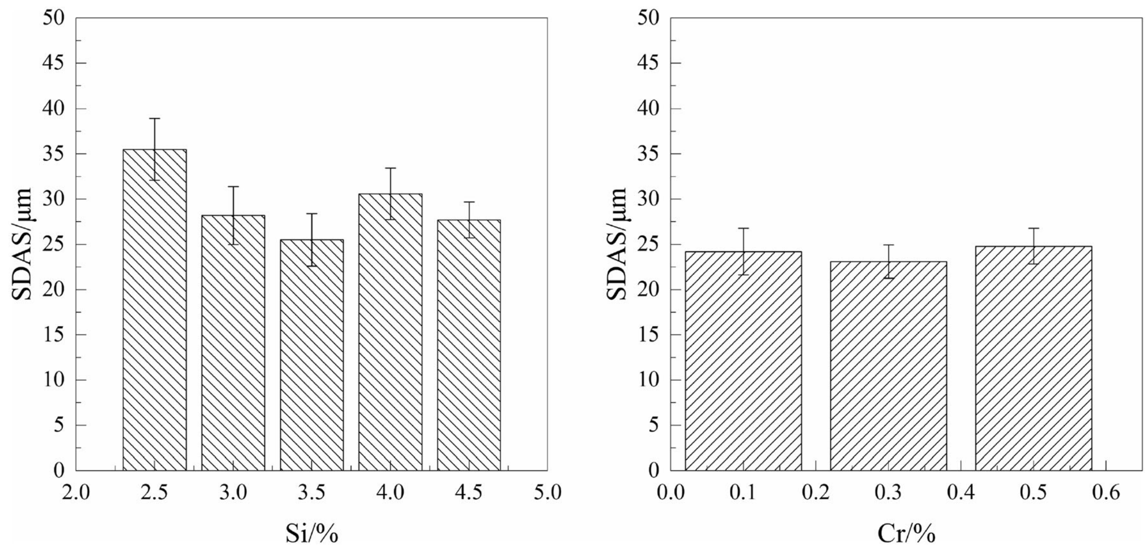


Fig. 8 Effect of Si and Cr elements on SDAS

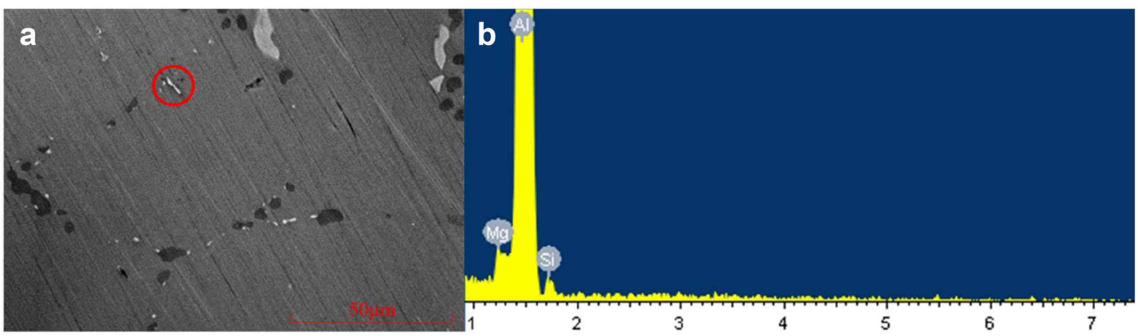


Fig. 9 Metallographic structure under scanning electron microscope **a** microstructure; **b** element composition

were improved slightly. There were casting defects such as microcracks and shrinkage pores, Fig. 10. Stress concentration is likely to occur at these defects, resulting in crack propagation, which will cause the material to break. When the Si content was 2.5 and 4.5%, the dimples were larger and deeper. There was a more obvious tearing rib. The material was not susceptible to plastic deformation, so the toughness of the material was better.

3.2.4 DSC Analysis

The results of differential thermal analysis showed that an exothermic peak appeared at about 300 °C during the heating of the 3.5%Si sample from 40 to 540 °C, corresponding to the *β*' strengthening phase, Fig. 11. The higher the solid solubility of Mg and Si in the matrix, the faster the diffusion of solute atoms in the matrix and the more uniform the distribution in the matrix, thus facilitating the precipitation of the *β*' phase. In addition, a large amount of Mg and Si atoms were enriched in the GP region, which caused lattice distortion. The Mg and Si atoms continued to be enriched and precipitate directly on the grain boundaries or on the screw dislocations to form the β' phase thus blocking dislocation motion, given by high strength and hardness. Then, the equilibrium β phase precipitated completely lost coherence with the matrix, which reduced the lattice distortion of the matrix and weakened the hindrance of dislocations, thereby reducing the strength and hardness of the alloy [12].

3.3 Effect of Different Cr Contents

The above analysis showed that the material had the highest strength when the Si content was 3.5%. The effect of Cr contents on microstructure and mechanical properties of aluminum alloy was studied. Therefore, the Si element was fixed to 3.5% in the composition design. Three elements of the Cr element were selected to be 0.1%, 0.3% and 0.5%, respectively.

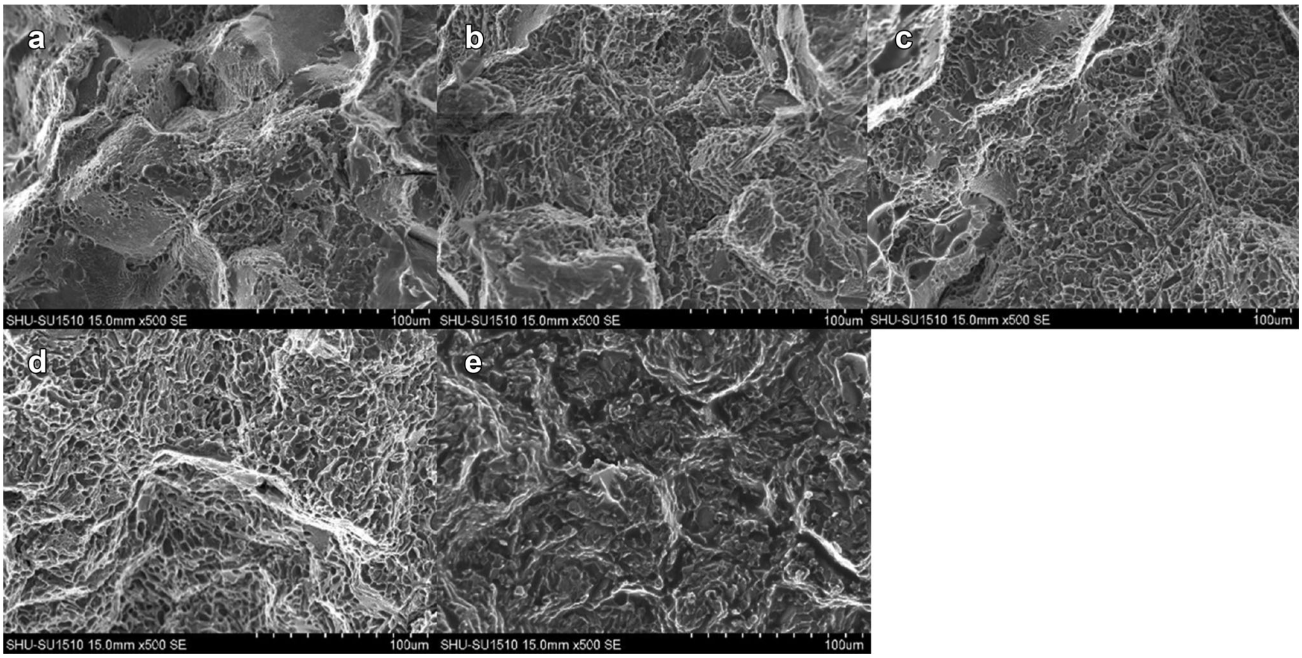
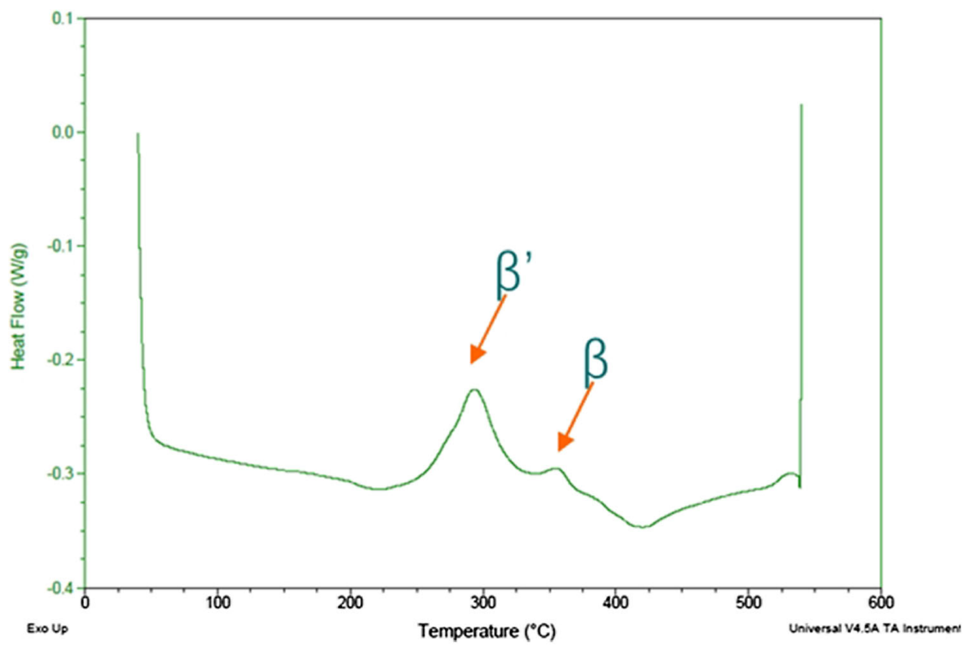


Fig. 10 Effect of Si contents on fracture morphology **a** 2.5%; **b** 3.0%; **c** 3.5%; **d** 4.0%; **e** 4.5%

Fig. 11 DSC curve of sample with 3.5% Si



3.3.1 Mechanical Properties

According to the above research, when Si was 3.5%, the strength of aluminum alloy was the highest. Due to the low elongation, the content of Mg element was adjusted to make the alloy have good comprehensive mechanical properties. The experiment was carried out by adding 0.1, 0.3 and 0.5% Cr elements to keep Si and Mg unchanged. Cr had the dual effects of dispersion strengthening and fine grain strengthening. Referring to the composition of some forged aluminum alloys, when the recrystallization and grain growth are limited at the same time, the Cr content is usually 0.1% to 0.4%. Further increase of Cr will significantly increase the hot cracking tendency, which is disadvantageous in cast aluminum alloys. Therefore, the maximum Cr content involved here was 0.5%. Then, the Brinell hardness and tensile test of samples with different Cr content were tested. Figure 12 presents the average

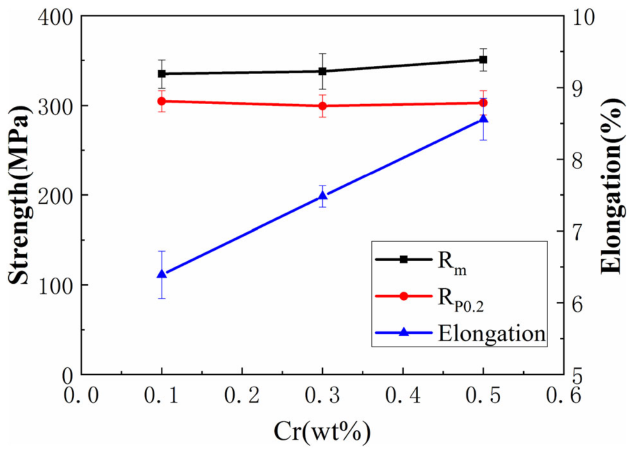


Fig. 12 Effect of Cr contents on mechanical properties

values of tensile strength, yield strength and elongation of different specimens.

When the content of Cr increased from 0.1 to 0.5%, the Brinell hardness did not fluctuate obviously, which indicated that the effect of Cr on the hardness of the alloy was not obvious. However, in Fig. 12, when the Cr content increased from 0.1 to 0.5%, the tensile strength and elongation of aluminum alloy increased obviously. The tensile strength and elongation were the lowest when Cr content was 0.1%. With the increase of Cr content, the tensile strength and elongation increased all the time and reached the maximum value when Cr was 0.5%. Compared with the previous experiments, the toughness of the material was improved. The experimental results showed that the method of adding Cr on the basis of 3.5% Si was effective and feasible. Although the elongation of the material can continue to increase, it is not suitable to add more Cr element due to the increase of hot cracking tendency.

3.3.2 Microstructure

The optical microstructure observed is given in Fig. 13. The eutectic Si after spheroidization is loose and the dendrites are coarse under the same magnification when the Cr content is 0.1%. The microstructure of the material became finer when the Cr content increased to 0.5%. The improvement in the mechanical properties of the alloy is closely related to these fine and uniform particles. The eutectic structure was also quantitatively calculated by IPP. The results showed that the proportion of eutectic structure was about 4%, which corresponded to the above results. It proved that this method had certain accuracy. These changes were due to the heterogeneous nucleation of Cr during solidification, thus achieving the effect of refining the grains. D.M. Jiang and other studies have shown that Cr is a typical disperse phase forming element in the alloy [13]. As in this experiment, exiguous AlMgSiCr and AlFeSiCr dispersion phases may be formed at grain boundaries, scanning electron microscopy (SEM) was used to observe the dispersed phase. The results showed that the white spots inside the red ring were dispersed phase and the corresponding energy spectrum analysis was on the right side, Fig. 14. These dispersed phases had high density and high thermal stability, pinning dislocations and grain boundaries during heat treatment and thermal deformation of alloys. It hindered dislocation rearrangement and grain boundary migration and inhibited the recrystallization of deformed grains and recrystallized grain growth [14]. The grain size became significantly smaller with the Cr contents increased. When the Cr contents was between 0.1 and 0.5%, the SDAS was about 24 μm, which got further reduced with the change in Si contents (the SDAS was above 25 μm.), Fig. 8. It had a certain strengthening effect on the alloy, also improved the toughness of the alloy. In addition, appropriate amount of Cr also improved stress corrosion resistance.

The addition of Cr to the aluminum alloy had the following three aspects of strengthening effect: First, solid solution strengthening effect was formed when Cr was dissolved in matrix; second, Cr could promote the transformation of AlFeSi phase from acicular β-AlFeSi phase to spherical α-AlFeSi phase [15]. The number of AlFeSi phases increased during this transformation. The α-AlFeSi phase and the dispersed phase could hinder the dislocation

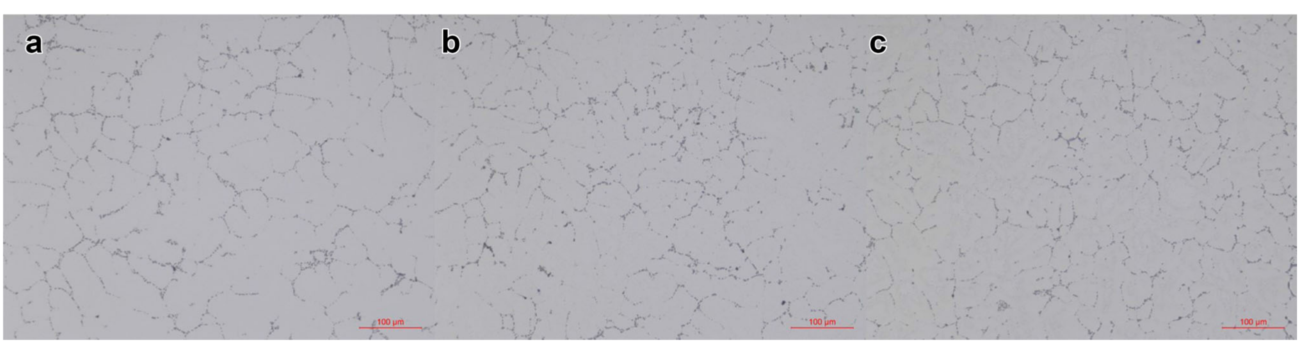


Fig. 13 Effect of Cr contents on microstructure **a** 0.1%; **b** 0.3%; **c** 0.5%

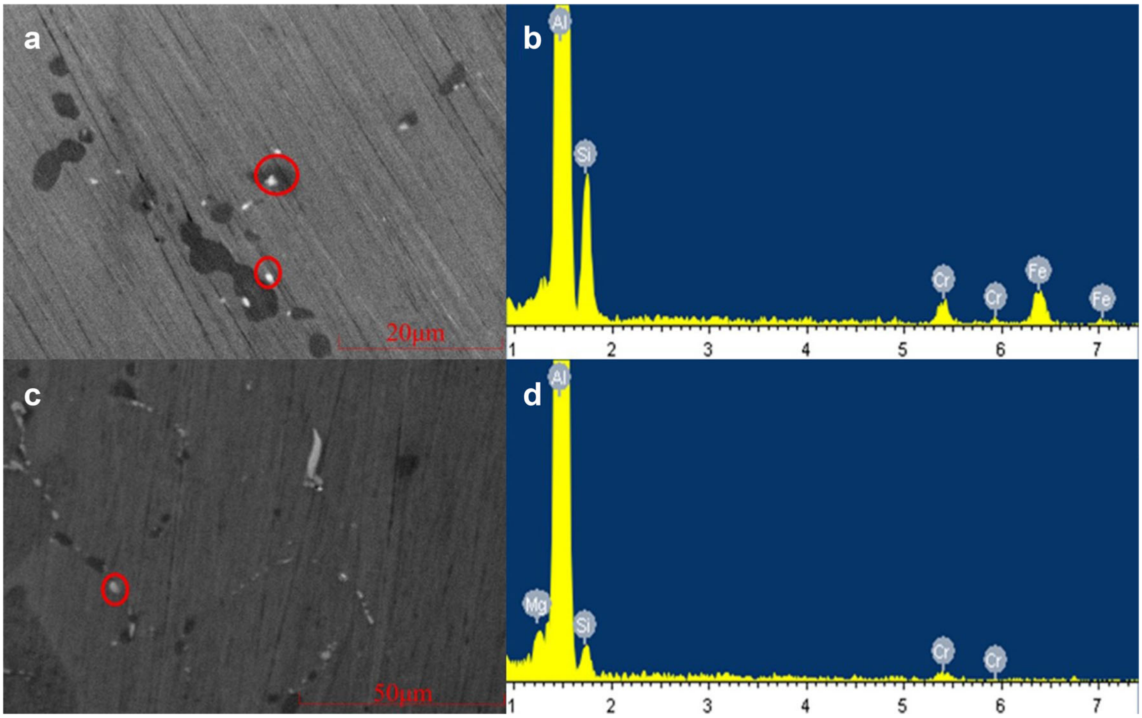


Fig. 14 Existence of dispersed phase **a** AlFeSiCr; **b** energy spectrum analysis of AlFeSiCr; **c** AlMgSiCr; **d** energy spectrum analysis of AlMgSiCr

slip during the deformation of the alloy, thereby producing dispersion strengthening effect. Finally, the α-AlFeSi phase, the AlMgSiCr and AlFeSiCr dispersion phase could strongly pin dislocation and grain boundaries during deformation processing and heat treatment, inhibiting deformation grain recrystallization and grain growth. Thereby fine grain size and fibrous unrecrystallized grains could still be obtained after the solution treatment of the alloy, which had good effect of grain strengthening and layer strengthening on alloy [16].

3.3.3 Tensile Fracture Morphology

Tensile test was carried out on three batches of samples with different Cr contents. The results showed that the elongation of the sample was obvious and the necking degree was different. The sections were gray and almost no metallic luster. It showed that the sample had good plasticity. The tensile fracture morphology of the T6 alloy was given. It could be seen that the tensile fracture of the alloy had a distinct dimple-like structure and exhibited typical ductile fracture characteristics, indicating that it had good toughness and ductility. From the comparison of the fracture morphology, Fig. 15, it could be seen that the dimples gradually became larger and deeper and the distribution was more uniform during the change of Cr contents from 0.1 to 0.5%. Because the dimples were large and deep and the more energy the material absorbed during the fracture process, the stronger the plastic toughness of the material. Therefore, the elongation of the material tended to rise slowly.

4 Conclusions

For Al–Si–Mg cast alloys with Si content between 2.5 and 4.5% it was found that:

With the increased of Si contents, the strength of aluminum alloy increased first and then decreased. The elongation developed inversely to the trend of the strength. The strength and hardness of the alloy reached the maximum value when the content of Si element was about 3.5%. At this Si content, the microstructure of the material distributed evenly. Mg_2Si improved the mechanical properties of the alloy as the main strengthening phase.

The strength and elongation of Al–Si–Mg aluminum alloys showed an upward trend with the increase of Cr contents from 0.1 to 0.5%. The microstructure changed to be uniformly distributed, and the dimples became larger and deeper gradually. The reason was that, Cr element had the ability to inhibit the recrystallization of the alloy, and the AlMgSiCr and AlFeSiCr phase had a dispersion strengthening effect. So the strength and toughness of the material got improved.

A large number of Mg and Si enriched in the GP zone resulted in lattice distortion and precipitated directly on the

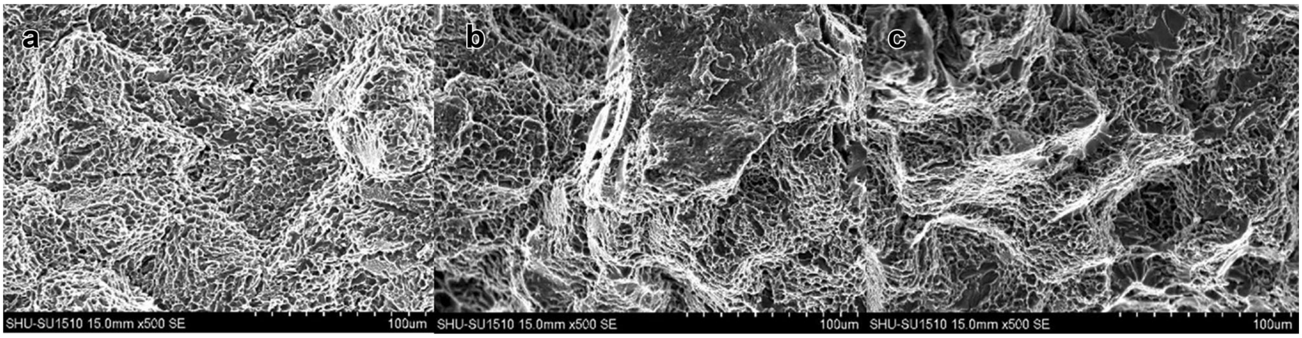


Fig. 15 Effect of Cr contents on fracture morphology **a** 0.1%; **b** 0.3%; **c** 0.5%

grain boundaries or on the screw dislocations to form β' phase. It hindered dislocation motion and exhibited high strength and hardness. This was the key to improve the mechanical properties of new cast aluminum alloys.

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