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Effect of Mg addition on microstructure and mechanical properties of Al-Si-Cu-Fe alloy with squeeze casting

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Abstract

In this work, the Al-10Si-2.5Cu-0.8Fe alloy was used as the base alloy to squeeze casting with different content Mg-10Al master alloy addition. The effects of microstructure and mechanical properties were investigated by XRD, OM, SEM, and tensile test analysis. The results show that with the increase of Mg addition, the morphology of eutectic Si in the alloy changes from strip to fiber and the size is obviously reduced. Al6Mg3FeSi6 phase in the microstructure gradually grows, and the splitting effect on the matrix structure is increased. The tensile strength and elongation of the alloy increased first and then decreased with the increase of Mg content. When the Mg content is 1.38%, the tensile strength of the alloy reached a maximum of 289 MPa and the elongation is 2.24%. The hardness of the alloy gradually increases. When the Mg content is 2.51%, the hardness reaches 121.8 HV. The cleavage surface in the fracture becomes fine with the increase of Mg content, the number of dimples increases, and the fracture mode transitions from quasi-cleavage fracture to brittle fracture.

1. Introduction

Al-10Si-2.5Cu-0.8Fe alloy is one kind of near eutectic high pressure die casting aluminum alloys. Due to its good fluidity and low shrinkage defects during casting, good corrosion resistance and wear resistance, it is widely used in the production of thin-walled automotive and aerospace parts [1–4]. In recent years, with the development of new energy vehicles, the requirements for reducing the weight of automobiles have gradually increased. Improving the strength of alloy is one of the main ways to reduce the weight of automobile parts [5, 6]. For Al-Si alloy casting, researchers often try to improve the microstructure and mechanical properties of the alloy by a method of adding micro-alloying elements [7–9]. The main alloying elements in aluminum alloys such as Cu, Mg, Sc, Sr, and Ti. Cu can form a CuAl2 phase in the aluminum alloy, which acts as a dispersion strengthening [10, 11]. A small amount of Sr can modify the eutectic silicon, which can achieve the effect of refining the grains [12, 13]. Zarif, M. studied the Al-5Si master-alloys with controlled Sr and/or P addition/s were produced using super purity Al 99.99% and Si 99.999% materials in an arc melter. Results indicate that, unlike P, Sr does not promote nucleation. Increasing Sr additions depressed the eutectic nucleation temperature [14]. Jian using high-intensity ultrasonic vibration refinement of eutectic silicon phase of aluminum A356 alloy. The results show that rosette-like eutectic silicon is formed during solidification of specimen treated with high-intensity ultrasonic vibration [15]. Yun found that electromagnetic vibration can refine the microstructure significantly. The refinement and migration of primary Si depended on the Lorentz force, gravity and the effective viscous force [16]. Mao found that a small amount of Eu can change the eutectic Si from a coarse plate to a fiber and significantly improve the mechanical properties [17].

The Mg content of the ADC12 aluminum alloy is 0.3% or less, and the strengthening effect is limited [18]. Yeom et al [19] improved the mechanical properties of the alloy by adding Mg and Al3Ca. Salleh, et al [20] studied the semi-solid microstructure and mechanical properties of Al-5Si-Cu with different Mg content. Researchers believe that Mg has a significant improvement in the mechanical properties of Al-Si alloys [21, 22]. Increasing the Mg content can significantly increase the possibility of Al8mg3fesi6 phase formation, and the
influence of various Mg contents on the Fe-rich phase is studied by reference. The results of the study indicate that the Mg content is 0.4–0.6 wt. % will form a script-like rich-Fe phase. However, there are few reports on the size and morphology of eutectic Si and Fe-rich phases with Mg addition Al-Si-Cu-Fe cast alloys. In this study, different amounts of Mg are added to the alloy of Al10Si2.5Cu0.8Fe (alloy composition similar to ADC12). The effect of Mg content on eutectic Si and Fe-rich intermetallic compounds was studied. The relationship between microstructure and mechanical properties was investigated, and the fracture mechanism of the alloy was discussed.

2. Experimental

The commercial Al-10Si-2.5Cu-0.8Fe aluminum alloy and Mg-10Al master alloy were used to prepare the target alloys. The prepared actual alloy compositions were measured using the M5000 direct reading spectrometer. The detailed chemical composition is listed in table 1. Differential thermal measurements of different Mg content alloys were carried out using the Netzsch STA-449F3 model TG-DSC thermal analyzer at the heating rate of 10 °C min⁻¹. The automobile engine bracket was chosen as the research component in this work, and it is shown in figure 1(a). The experiment was carried out on the SCH-350A squeeze casting machine with the pouring temperature of 675 °C, squeeze pressure of 130 MPa and the injection speed of 0.1 m s⁻¹. Phases composition of the alloy was detected using a Panalytical X-Pert Pro model x-ray diffractometer. The scanning speed is 9° min⁻¹ and the scanning range is 20° to 90°. The 1% HF solution is used as the etching solution, and the etching time is 5–10s. The time when deep etching is performed in 12 h. Microstructure and fracture morphology were observed using OLYMPUS-GX7 optical microscope and the FEI Sirion-200 model scanning electron microscope. A part of the automobile engine bracket casting was cut into a tensile specimen according to the standard of ASTM E8/E8M. The sampling position and the pulling size of the tensile specimen are shown in figure 1(b). Five tensile specimens were processed for each set of processes. The tensile test was carried out on the WDW-200 electronic universal testing machine with a strain rate of 10⁻³ s⁻¹. Vickers hardness test was performed using Hv-1000 tester with a load of 50N.

3. Results and discussion

In order to further clarify and analyze the effect of adding Mg content on the smelting and solidification process of the alloys, the heating process of adding Mg contents were studied. Figure 2 shows the DSC curves for Mg

| Alloy     | Target Mg | Actual Mg | Si  | Cu  | Fe  | Mn | Al  |
|-----------|-----------|-----------|-----|-----|-----|----|-----|
| Base alloy| 0.2       | 0.18      | 10.44|2.35 |0.67 |0.20| Bal. |
| Base-M0.8 | 0.8       | 0.77      | 10.32|2.30 |0.64 |0.19|     |
| Base-M1.4 | 1.4       | 1.38      | 10.35|2.41 |0.70 |0.21|     |
| Base-M2.0 | 2.0       | 2.03      | 10.31|2.46 |0.67 |0.21|     |
| Base-M2.6 | 2.6       | 2.51      | 10.35|2.38 |0.58 |0.20|     |
content of 0.18%, 0.77%, and 1.38%, respectively. It can be observed from figure 2 that the melting curve is smooth when the Mg content is 0.18%, and the phase transition occurs at 538°C. This is the melting temperature of the eutectic Si. When the temperature rises to 584.2°C, α-Al and eutectic silicon are completely melted. With the Mg content increases, the peak point gradually shifts toward the low-temperature side. The peak temperature was 574°C when the Mg addition amount was 1.38%. And 10.2°C is reduced compared to base alloy. At the same time, when the Mg content is 1.38%, there are multiple turning points in the curve. It can be observed from figure 2 that the turning point temperatures are 547°C and 561°C, respectively. 547°C and 561°C are the melting temperature and the complete melting temperature of the Mg2Si phase, respectively. More eutectic Mg2Si phases appear in the microstructure. As the Mg content increases, the melting point of the alloy decreases [23].

Figure 3 shows the XRD patterns with different Mg addition. The main phases in the base alloy are α-Al, eutectic Si and Al2Cu. And the Fe-rich phase is mainly in the form of Al5FeSi phase. As the amount of Mg added increases, the peaks in the XRD pattern gradually change. It is more obvious that the two peaks appear between 30° and 45° when the Mg content is 1.38%. The Al3FeSi phase disappears, and the Al8Mg3FeSi6 phase and the Mg2Si phase appear. In order to observe the new phase formed by adding the Mg-Al master alloy more clearly, the diffraction angle range was selected from 25° to 50° for analysis (figure 3(b)). It can be clearly seen from figure 3(b) that when the Mg content is 2.51, the Mg2Si phase and the Al8Mg3FeSi6 phase are detected.

Figure 4 shows the microstructure with different Mg additions at low magnification. And further analysis with the XRD patterns of figure 3. The microstructure in the base alloy is mainly composed of α-Al, eutectic Si, CuAl2, Mg2Si, and Al3FeSi phase. It can be observed from figure 4(a) with the Mg content of 0.18% that the α-Al phase has not obvious grain boundary in the microstructure. The eutectic Si is distributed around the α-Al, some even penetrate the entire α-Al grain, which increases the splitting effect on the matrix structure. After the addition of magnesium, a distinct grain boundary appears in the α-Al phase, and the gray eutectic Si is distributed around the grains. This is mainly due to the suppression of the growth of eutectic Si after the addition of Mg. Moreover, the eutectic Si and α-Al form a good wetting effect during the solidification process, so that the grain boundaries become continuous and complete. When the magnesium content is increased to 1.38% and
2.03%, the α-Al grain boundaries become clearly, as shown in figures 4(c) and (d). And the eutectic Si and eutectic Mg2Si are distributed around the grains in the form of eutectic groups. When the Mg content is increased to 2.51%, the microstructure is shown in figure 4(e). A long strip phase appeared in the microstructure. The grain size is reduced from 19.8 μm in a content of 0.18% Mg to 11.3 μm in a content of 1.38% Mg. The change about the grain α-Al size is shown in figure 5.

The mechanical properties of the alloys are affected by the morphology and size of the primary α-Al and some second phases. Therefore, in order to analyze the influence of the amount of Mg addition on the eutectic Si and Fe-rich intermetallic phase, the microstructure of the different Mg contents are observed with high magnification. It can be seen from figure 6(a) that the eutectic Si is distributed around the α-Al grain in the form of long strips, and no obvious grain boundaries are observed in α-Al. The eutectic Si is mainly embedded in α-Al grain. And a small amount of CuAl2 phase is also observed. When the Mg content is 0.77%, the size of the strip-shaped eutectic Si in the microstructure is refined as shown in figure 6(b), but the morphology does not change significantly. When the Mg content is increased to 1.38%, the size and morphology of the eutectic silicon are mainly distributed around the α-Al grain in a fibrous or granular form, and the size is remarkably refined. The splitting effect on the matrix is reduced. At the same time, the α-Al grain boundary is clear, which is mainly due
to the preferential formation of \( \alpha \)-Al grain in the solidification process of the molten metal. A small amount of gray phase with a small size appeared in the microstructure. It was speculated that the phase was \( \text{Al}_8\text{Mg}_3\text{FeSi}_6 \) phase after XRD and metallographic microstructure analysis. When the Mg content is 2.51%, the morphology of the \( \text{Al}_8\text{Mg}_3\text{FeSi}_6 \) phase is mostly continuous or semi-continuous strip. It is similar to eutectic Si in the matrix alloy, which increases the splitting effect on the substrate [24]. At the same time, since the melting point of the Fe-rich phase is higher, it is formed in preference to the \( \text{Mg}_2\text{Si} \) phase during solidification, so the content of the \( \text{Mg}_2\text{Si} \) phase in the microstructure is reduced. About the eutectic Si is refined after the addition of Mg, there are two main reasons. On the one hand, after adding different contents of magnesium, eutectic Si is distributed between the solid phase and the liquid phase during solidification. Mg forms a \( \text{Mg}_2\text{Si} \) phase with Si, which hinders the growth of eutectic Si. On the other hand, the \( \text{Mg}_2\text{Si} \) phase is distributed at the solid-liquid interface. The degree of undercooling is increased during the solidification process, so that the grain size is refined.

In order to further determine the morphology and distribution of each phase, the alloy was subjected to EDS analysis and surface distribution scanning. Figure 7 shows the morphology of the main phases after the addition of 1.38% magnesium. And table 2 listed the main phases calculated from EDS analysis from figure 6. Combine with XRD patterns, EDS analysis and microstructure, it is known that the microstructure of different alloys mainly includes \( \alpha \)-Al, eutectic Si, \( \text{Al}_3\text{Cu} \) phase, \( \text{Al}_8\text{Mg}_3\text{FeSi}_6 \) phase and \( \text{Mg}_2\text{Si} \) phases.

Figure 8 shows the distribution of major elements in the microstructure of the alloy with Mg content of 1.38%. Figures 8(b)–(f) are the distribution of Al, Si, Mg, Cu and Fe elements, respectively. It can be seen from figure 8 that there is a coincidence position between the Mg element and the Si element distribution. This phase...
is the Mg$_2$Si determined by XRD patterns and EDS. In addition, the Cu element in the microstructure forms a low melting point phase of CuAl$_2$ with the Al element.

To further observe the morphology of the various phases in the microstructure, samples of different Mg additions were deeply etched in 0.5% hydrofluoric acid for 12 h. It can be seen from figure 9(a) that the morphology of the eutectic Si in the base alloy is mainly coarse and large plate. When the Mg content is increased to 0.77%, the eutectic Si morphology remains in the form of flakes after deep etching. But the size is reduced compared to the base alloy. When the Mg content continues to increase to 1.38% and 2.03%, the morphology of the eutectic Si becomes finer and appears fibrous. The morphology of the eutectic Si phase does not change significantly with 2.51% addition, but a large number of long Al$_8$Mg$_3$Fe$_6$Si$_6$ phase appear in the microstructure.

The tensile strength, elongation and hardness of the squeeze-cast alloy with different magnesium contents are shown in figure 10. With the increase of Mg addition, the tensile strength and elongation first increase and then decrease. When the Mg content is 1.38%, the tensile strength of the alloy reaches a maximum of 289 MPa. Mg added to the alloy will form the Mg$_2$Si phase to consume a portion of the Si. Due to the significant transformation of the eutectic Si morphology in the alloy, the splitting of the matrix is reduced. It is well known that the smaller the grain size, the higher mechanical properties of the alloy. When the Mg content is 2.51%, the tensile strength of the alloy is reduced to 265 MPa. The main reason is that the appearance of the strip-like Al$_8$Mg$_3$Fe$_6$Si$_6$ phase in the microstructure increases the splitting effect of the matrix α-Al, which reduces the mechanical properties of the alloy. The elongation of the alloy reached a maximum of 2.24% at a magnesium content of 2.03%, which was 87% higher than that of the base alloy. The Vickers hardness increases as the Mg content increases. The maximum Vickers hardness is 121.8HV. This trend is due to an increase in the Mg$_2$Si phase in the microstructure as the Mg content increases.

Figure 11 shows the SEM morphology of squeeze-cast alloy fractures with different Mg contents. The tensile fracture morphology of the base alloy is shown figure 11(a). There are larger cleavage planes and cleavage steps in the fracture morphology, and a small number of dimples are also present. Combined with the mechanical properties of figure 10, the elongation under this condition is 1.2% and does not show good plasticity. It is indicated that the fracture mode of the base alloy under the squeeze-cast condition is quasi-cleavage fracture. When the Mg content increased to 0.77%, the cleavage plane and the cleavage step in the fracture morphology are refined, but a large number of dimples were not observed. It can be seen that there are tear ridges in the

### Table 2. The main phases and morphology calculated from figure 6 EDS analysis.

| Point | Al  | Si  | Cu  | Mg  | Fe  | Phase               |
|-------|-----|-----|-----|-----|-----|---------------------|
| A     | 62.29 | /   | 37.71 | /   | /   | Al$_2$Cu            |
| B     | 64.93 | 21.66 | /   | 8.06 | 5.34 | Al$_8$Mg$_3$Fe$_6$Si$_6$ |
| C     | 51.73 | 47.99 | /   | 0.29 | /   | Eutectic Si         |
| D     | 1.02  | 35.61 | /   | 63.36 | /   | Mg$_2$Si            |

Figure 8. Elements mapping with squeeze casting of 1.38% Mg content.
fracture morphology. This content does not change the fracture form of the alloy, but the mechanical properties have improved. It also can be seen from figure 11(d) that the area and number of cleavage planes in the fractures are significantly reduced. The morphology of the fractures is similar to that of the fibrous eutectic Si in the microstructure with 2.03% Mg addition. It is indicated that the fracture mainly occurs in the concentration of fibrous eutectic Si. The refinement of eutectic Si also improves the mechanical properties of the alloy. This is consistent with the microstructure of figure 6 and the mechanical properties of figure 10. As the Mg content continues to increase, Al, Si, Mg and Fe in the microstructure form an Al8Mg3FeSi6 phase. Due to the presence of the coarse flake-rich Fe phase, the splitting action on the matrix α-Al is again increased. When the external force acts, the stress concentration preferentially forms a crack source, which promotes the crack initiation and fracture.

The fracture morphology can illustrate the fracture modes of the alloy. The cross-section microstructure can more clearly observe the fracture information. Figure 12 shows the microstructure of the fracture section (vertical fracture direction) after the tensile fracture of the alloy with different Mg contents. It can be seen from the cross-sectional microstructure of the alloy fracture. There is a coarse plate-like eutectic Si at the leading edge of the fracture morphology. The fracture did not pass through the α-Al matrix. It is indicated that the crack source position is a coarse plate-like eutectic Si. When the Mg content is increased to 1.38%, the eutectic Si phase in the alloy microstructure is refined, and a large amount of eutectic Si fracture occurs in the fracture. As can be clearly observed in figure 12(c), The broken portion has been peeled off from the matrix structure. The crack source is mainly caused by the accumulation of eutectic silicon, and the fracture occurs when the external force

Figure 9. Scanning electron micrograph after deep etched (a)–(e) samples with respective Mg content of: 0.18, 0.77, 1.38, 2.03, 2.51 (wt%).

Figure 10. Mechanical properties of as-cast alloys with different magnesium contents.
continues to increase. When the Mg content continues to increase, the flaky Al₈Mg₃FeSi₆ phase in the microstructure increases, and it can be seen from figures 12(d) and (e) that the fracture site is concentrated at the Fe-rich phase.

4. Conclusion

(1) As the Mg content increases, the morphology and size of eutectic Si in the alloy change significantly. The morphology changes from coarse plate to fiber and the size is significantly smaller. When the Mg content reaches 1.38%, the size of the Si phase is minimized.

(2) Tensile strength and elongation first increase and then decrease as the Mg content increases. When the magnesium content is 1.38%, the tensile strength of the alloy reaches a maximum of 289 MPa; and the elongation reaches a maximum of 2.24% at Mg content of 2.03%.

(3) The cleavage plane in the fracture morphology become fine with the increase of Mg content. The number of dimples increases, and the fracture mode changes from quasi-cleavage fracture to brittle fracture. As the Mg
content increases, a long strip-like Al8Mg3FeSi6 phase is formed in the alloy structure, which increases the splitting action on the matrix and causes the fracture mode to transform to brittle fracture again.

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