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Effects of Al-5Ti-0.62C-1.07La intermediate alloy on the microstructure and mechanical properties of A356 aluminum alloy

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Abstract

The physical characters that belong to hypo-eutectic Al-Si alloys are affected by certain important factors including the dimension, distribution together with structure of eutectic Si crystals together with primary \( \alpha \)-Al. In this paper, A356-x Al-5Ti-0.62C-1.07La (x = 0, 4, 5, 6, 7 wt%) alloys are prepared by mechanical stirring. The effects of Al-5Ti-0.62C-1.07La intermediate alloy on the microstructures and mechanical properties of A356 alloy are investigated. Results show that the primary \( \alpha \)-Al was significantly refined by Al-5Ti-0.62C-1.07La intermediate alloy. The secondary dendrite arm space (SDAS) of unrefined \( \alpha \)-Al is approximately 40 \( \mu \)m. When the substance of Al-5Ti-0.62C-1.07La intermediate alloy is 6 wt%, SDAS declines to 10 \( \mu \)m. In addition, the component part of eutectic Si turns from thick acicular/schistose to short rod-like together with a section of pellets. Adding 6 wt% Al-5Ti-0.62C-1.07La intermediate alloy, A356-T6 alloy obtained the best tensile function and hardness. The ultimate tensile strength (UTS), elongation (El) together with Vickers hardness (HV) are 183.5 MPa, 8.2% and 62.3, which is increased by 30.3%, 95.2% and 38.1%, respectively. Furthermore, the variation in mechanical properties change with the development of micro-structure.

1. Introduction

A356 aluminum alloy has high strength, low density and good casting performance, so it is widely used in many industries, such as the automobile, aircraft, aerospace and so on.[1]. The mechanical features of A356 alloy without refinement together with modification are poor. There are coarse \( \alpha \)-Al grains and acicular together with stripe eutectic Si in its structure [2, 3]. Therefore, in the melting and casting process of A356 alloy, refinement and modification are needed. Refining and modification process can not only obtain uniform and fine grains, but also improve the shape together with magnitude of eutectic Si, reduce the segregation of A356 alloy structure, and solve the casting defects for instance stoma, crack together with feather crystal [4].

In the existing production technology, grain refiners (for instance Al-B, Al-Ti-C, Al-Ti-B, together with other intermediate alloys [5]) and Si modifier (such as Na, Sr and RE [6]) are often added to A356 alloy respectively to achieve better granule purification and modification effect [7]. However, it’s difficult to control the refining and modification effect, because of the complexity of smelting process [8]. For this reason, many scholars have carried out a lot of research work. For example, Liu et al prepared Al-3B-55Sr master alloy by in-situ reaction method [9]. Qiu et al prepared Al-6Sr-7La master alloy with rare earth elements and Sr as refining and modifying elements respectively [10]. These intermediate alloys can not only modify eutectic Si phase, but also refine \( \alpha \)-Al of Al-Si alloy. However, the interaction between Sr and B will inevitably produce SrB6 compound in the smelt, which enormously reduces the effect of refining and modification of Al-Si alloy [9]. For the sake of making up for the deficiency of the master alloy containing Sr and B elements, Rao et al[11] together with Zhao et al [8] have successively developed the Al-Ti-C-Sr intermediate alloy, and their refining and modification effects have been studied. It is shown that the TiC pellets in the Al-Ti-C-Sr can be used as the heteromorphic
nucleus of primary $\alpha$-Al, and $\text{Al}_4\text{Sr}$ can provide the Sr for modification Prime. It was found in the previous study \[12\] that the supplement of $\text{La}_2\text{O}_3$ and the rest rare earth oxides in the course of in-situ reactive synthesis about $\text{Al-Ti-C}$ intermediate alloy reduce the reaction heat of the alloy, enhance the wettability of C as well as Al flux, together with facilitate TiC pellets' construction, but also manufacture a novel $\text{Al-Ti-C-La}$ intermediate alloy with good refining effect for industrial pure aluminum. This article illustrates that the novel $\text{Al-Ti-C-La}$ intermediate alloy deal with the A356 alloy with the change of the addition amount on the refinement and modification which is about A356 alloy, in the meanwhile, the influence of the microstructure together with mechanical characters of A356 alloy was discussed. It is of great use to the refinement and modification of A356 alloy and the preparation of TiC and $\text{Al}_3\text{Ti}$ particle reinforced A356 Composite \[13, 14\].

2. Materials and experimental procedures

In this paper, the chemical ingredient of A356 alloy applied is shown in table 1. Al-5Ti-0.62C-1.07La intermediate alloy is self-made, in the meanwhile, its preparation method has been described in literature \[12\]. Firstly, different content (weight percentage) which belongs to Al-5Ti-0.62C-1.07La intermediate alloy is put in the $730^\circ\text{C}$ A356 alloy melt, adding the additive amount of 4 wt%, 5 wt%, 6 wt% together with 7 wt% partly (Note: the sample number and constitution of A356 alloy are shown in table 2). The master alloy is fully dissolved by holding for 10 min, and uniformly distributed in the A356 alloy melt by mechanical stirring, and then poured into the metal mold (preheating temperature $200^\circ\text{C}$) as shown in figure 1(a). Then, the samples were taken, and after rough grinding, fine grinding and burnishing, the superficials of the specimen was corroded by Keller reagent. The micro-structure of the specimen was featured by SEM (JSM-7500). The Secondary Dendrite Arm Space (SDAS) together with the eutectic Si's size was gauged by the Image-Pro plus software.

In order to study the affect, which is from Al-5Ti-0.62C-1.07La intermediate alloy that is on the mechanical features of A356-T6 alloy, hardness test and tensile experiment that is at room temperature were enforced. Firstly, the T6 heat-treatment was in progress on the A356 alloy, which could be divided into solution treatment ($535 \pm 5^\circ\text{C}, 5\text{ h}, \text{water cooling}$) and artificial aging ($160 \pm 5^\circ\text{C}, 5\text{ h}, \text{air cooling}$). Then, the Vickers hardness of samples were measured by hardness tester (HBRVU-187.5). Thereinto, five hardness measurements were taken for each sample, and an average value was reported to improve the reliability of the results. Afterwards, according to GB/T228.1-2010, the samples were processed into a national standard tensile sample, and the size of the tensile sample is shown in figure 1(b). Moreover, mechanical performance experiment should be conducted at the velocity of 0.5 mm min$^{-1}$ on an AGS-X tensile machine. Finally, the fracture of tensile test pieces was analyzed by SEM, and the break principle was discussed.

### Table 1. Chemical ingredient of the various base A356 alloy.

| Alloy | Elements (wt%) |
|------|----------------|
|      | Si  | Mg  | Fe  | Cu  | Mn  | Ti  | Zn  | Al   |
| A356 | 7.45| 0.457| 0.369| <0.001| 0.121| 0.011| 0.012| Bal. |

### Table 2. A356 alloy amount with diverse content of master alloy.

| Alloy Num. | A356-x Al-5Ti+0.62C-1.07La (wt%) | Composition of theoretical calculation (wt%) |
|-----------|---------------------------------|---------------------------------------------|
| #1        | 0                               | TiC 0 Al3Ti 0 La 0                           |
| #2        | 4                               | 0.124 0.272 0.043                           |
| #3        | 5                               | 0.155 0.341 0.054                           |
| #4        | 6                               | 0.186 0.409 0.064                           |
| #5        | 7                               | 0.217 0.477 0.075                           |
3. Results and discussion

3.1. Micro-structure of Al-5Ti-0.62C-1.07La Intermediate Alloy

Figure 2 illustrates that the micro-structure of Al-5Ti-0.62C-1.07La intermediate alloy. From figure 2(a), it is thus clear that Al-5Ti-0.62C-1.07La intermediate alloy is mainly composed of Al$_3$Ti phase, Ti$_2$Al$_2$La phase and TiC phase dispersed on the Al matrix. The shape of Al$_3$Ti phase is long strip or needle, with a length of 50–100 μm; Ti$_2$Al$_2$La phase is bright white irregular block or plate, with a size of 30–50 μm. TiC phase was distributed in clusters or pellets on the Al basal body or crystal boundary, with the size between 0.15–0.5 μm, as shown in figure 2(b). As can be percieve from figures 3(a) and (b) that TiC particles’ shape is basically hexagonal, and there are also pentagonal shapes with little difference in size. TiC particles gather together to form TiC clusters. Figure 3(c) demonstrates the designated region electron diffraction pattern which is homologous to TiC particles in figure 3(a), and [031] is its crystal band axis. Figure 3(d) shows the crystal plane spacing on the TiC (111) plane. When the incident electron beam is incident parallel to the TiC [031] crystal band axis, it can be clearly seen that the atomic layer on the TiC (111) plane is distributed in parallel, and the spacing between the atomic layer and the atomic layer is 0.26 nm. In this paper, the dynamics together with thermodynamics of the synthesis of Al-Ti-C-La intermediate alloy have been systematically considered [12].
3.2. Influence of Al-5Ti-0.62C-1.07La Intermediate Alloy on Micro-structure of A356 Alloy

Micro-structure of $\alpha$-Al in as-cast A356 alloy of different Al-5Ti-0.62C-1.07La intermediate alloy content is shown in figure 4. From figures 4(a)–(b), in the A356 alloy, 4 wt% Al-5Ti-0.62C-1.07La intermediate alloy is used for purification and improvement, $\alpha$-Al is transformed from coarse dendrite to small dendrite, some of which are transformed into spherical and distributed near the small dendrite. With the increase of Al-5Ti-0.62C-1.07La intermediate alloy (see figure 4(c)) that the size of $\alpha$-Al phase changes obviously, that is, the spherical $\alpha$-Al phase increases, and the dendritic $\alpha$-Al phase almost does not exist. When the addition amount reaches 6 wt%, the $\alpha$-Al phase is almost spherical (see figure 4(d)). As the amount of Al-5Ti-0.62C-1.07La intermediate alloy supplement achieves 7wt%, most of the $\alpha$-Al phase is still globular. Figure 4(f) shows the average size of secondary dendrite arm spacing (SDAS) in different A356 alloys. It was found that the average size of the #4 A356 alloy was minimized when Al-5Ti-0.62C-1.07La intermediate alloy of 6 wt% was added, in the meanwhile, the SDAS size of the intermediate alloy was diminished largely, which indicates that the supplement of 6 wt% Al-5Ti-0.62C-1.07La intermediate alloy has better refining effect.

SEM characterized the microstructure of eutectic Si in as-cast A356 alloy which is with diverse contents of Al-5Ti-0.62C-1.07La intermediate alloy, as shown in figure 5. Comparing with figures 5(a)–(d), when Al-5Ti-0.62C-1.07La intermediate alloy is added into A356 alloy, the morphology together with size of eutectic Si abate obviously. Especially when the supplement quantity reaches 6 wt%, the composition of eutectic Si turns from coarse schistose and acicular to short rod-like together with graininess. Nevertheless, when the amount of supplement keeps going up to 7 wt%, certain fibre eutectic Si set out to coarsen into coar needle-like as well as microbead (see figure 5(e)). It is clearly from figure 5(f) that the mean size of eutectic Si in A356 alloy which is in place with the raise of Al-5Ti-0.62C-1.07La intermediate alloy content ranging from 4 wt% to 7 wt% is
substantially declined, in which the average size of eutectic Si in #4 A356 alloy is 4 μm, which shows that the supplement of 6 wt% Al-5Ti-0.62C-1.07La intermediate alloy has better modification effect on A356 alloy.

As is known that Al-based alloy melts with great speed after adding aluminum melt, in the meanwhile, a plenty of α-Al heterogeneous nucleating granules or Si modified elementary substance are released [15]. In this paper, adding a certain quantity of Al-5Ti-0.62C-1.07La intermediate alloy into A356 alloy melt, the TiC, Al₃Ti and Ti₂Al₂0La will be released with the dissolution of aluminum matrix. The affect of TiC together with Al₃Ti granulation on the heterogeneous nucleation of α-Al pellet has been covered together with verified by other researchers [16–18]. It has been reported that Ti₂Al₂0RE can not exist stably in the aluminum alloy melt [19, 20], it will dissolve and provide a lot of RE for the aluminum melt [21]. A large number of research reports have

![Figure 4. Micro-structures and SDAS of α-Al in as-cast A356 alloy with various dosage of Al-5Ti-0.62C-1.07La intermediate alloy: (a) unrefined; (b) 4wt%; (c) 5wt%; (d) 6wt%; (e) 7wt%; (f) SDAS.](image)
confirmed that RE has a good modification effect on eutectic Si by forming nano rare earth phase \[22\] or inhibiting Si twin growth \[23\]. Therefore, it can be seen from table 2 that as the addition of Al-5Ti-0.62C-1.07La master alloy increases, more and more TiC, Al\textsubscript{4}Ti and Ti\textsubscript{2}Al\textsubscript{12}La will be contained in A356 alloy melt. Theoretically, the more TiC and Al\textsubscript{4}Ti are, the more particles will promote the heterogeneous nucleation of \(\alpha\)-Al grains in A356 alloy; similarly, the more Ti\textsubscript{2}Al\textsubscript{12}La is, the more La elements it provides for aluminum melt. Therefore, the addition of Al-5Ti-0.62C-1.07La master alloy increased from 4 wt\% to 6 wt\%, and the secondary dendrite arm space (SDAS) and eutectic Si size of A356 alloy decreased greatly. This is in good agreement with the results shown in figures 4 and 5. However, when the addition amount of Al-5Ti-0.62C-1.07La master alloy reaches 7 wt\%, the coarsening degree of SDAS and eutectic Si increases. The main reason may be that when the
addition amount of Al-5Ti-0.62C-1.07La master alloy exceeds 6 wt%, there will be excessive Ti produced by the dissolution of Al3Ti in the melt [15], while the titanium silicide formed by Ti and Si not only damages the nucleation efficiency of Al3Ti and TiC [24, 25], but also the modification of Si by La is affected. Nevertheless, as there is no direct experimental evidence, the theoretical analysis is a reasoning model, so there will be further research in the near future.

The microstructure of A356-T6 alloys with diverse contents of Al-5Ti-0.62C-1.07La intermediate alloy (see in figure 6). After T6 thermal treatment, the morphology of eutectic Si changed clearly. After solution treatment of A356 alloy embodying Al-5Ti-0.62C-1.07La intermediate alloy, acicular / lamellar eutectic Si was transformed into fine spheroidized structure at the mass fraction of 4 wt%-7 wt%, separately. As the supplement quality of Al-5Ti-0.62C-1.07La intermediate alloy is 6 wt%, the eutectic Si of A356 alloy basically changes into granulate or spherical, with the minimum size and the average size is 2.5 μm. This change in size and morphology significantly reduces the corresponding stress concentration of eutectic Si, enhancing the mechanics behaviour of the alloy [26].

3.3. Effects of Al-5Ti-0.62C-1.07La Alloy on Mechanical Properties of A356 alloy

It demonstrates that the affect of various content of Al-5Ti-0.62C-1.07La intermediate alloy on ultimate tensile strength (UTS) as well as elongation of A356-T6 alloy in figure 7. As seen in figure 7 that UTS together with elongation without refined and modified A356-T6 alloy are 140.8 Mpa and 4.2%, respectively. When the mass content of Al-5Ti-0.62C-1.07La intermediate alloy is 4 wt%, 5 wt% together with 6 wt% separately, UTS along with elongation raise gradually. Especially when the content of Al-5Ti-0.62C-1.07La intermediate alloy is 6 wt%, the ultimate tensile strength together with rate of elongation achieve the maximum value, which are 183.5 Mpa and 8.2% respectively. Compared with the A356-T6 alloy without refining modification, they are increased by 30.3% and 95.2% respectively. However, the supplement of Al-5Ti-0.62C-1.07La intermediate alloy continued to reach 7 wt%, and the tensile strength and elongation decreased slightly, which may be owing to the augment of α-Al together with eutectic Si size after excessive refinement and modification of Al-5Ti-0.62C-1.07La intermediate alloy.

Figure 8 shows the Vickers rigidity of A356-T6 alloys with diverse Al-5Ti-0.62C-1.07La intermediate alloy content. The outcomes make known that as the raise of the content which is from 4 wt% to 7 wt%, the hardness increases gradually and then decreases. The A356 alloy refined by 6 wt% Al-5Ti-0.62C-1.07La intermediate alloy possesses the maximum hardness of 62.3, which correspond to 38.1% enhancements compared with that of the unreined alloy.

The fracture surface of A356-T6 alloy with diverse content of Al-5Ti-0.62C-1.07La intermediate alloy, which is illustrated in figure 9. There are a good deal of cleavage surfaces and steps on UTS of the unreifne A356-T6 alloy which is shown in figure 9(a). These large cleavage surfaces are connected with each other through the tearing edge, and there are large-scale cracks and secondary cracks on the tearing edge. In place with the raise of Al-5Ti-0.62C-1.07La intermediate alloy, the fracture dimples of A356-T6 alloy are increasing, the cracks and secondary cracks are decreasing, along with the fracture mode is converting from quasi-cleavage to ductility fracture. When the supplement quantity of Al-5Ti-0.62C-1.07La intermediate alloy is 6 wt%, the fracture almost exists in the form of dimples. These fracture dimples exist between the tearing edges. At this time, there are basically no cleavage surfaces and steps, nor large-scale cracks and secondary cracks, which is shown in figure 9(d). The needle-like eutectic Silicon in A356 alloy was modified into short rod shape after refinement and modification by a appropriate quantity of Al-5Ti-0.62C-1.07La intermediate alloy, together with further transformed into fine particle shape after T6 heat treatment. The influence of eutectic Si on the cleavage of Al basal body is significantly reduced, and the stress of granular eutectic Si is greater than that of short rod or needle eutectic Si [27]. At the same time, the eutectic Si, as the reinforcement phase, can hinder the crack growth [6], consequently, the mechanical characters of A356-T6 alloy have been extensively enhanced. In place with the supplement quantity of Al-5Ti-0.62C-1.07La intermediate alloy raised to 7 wt%, then the mechanical characters of A356-T6 alloy decreased slightly due to over refinement, the fracture mode was still dominated by ductile fracture, as shown in figure 9(e).

4. Conclusions

The influence of various quantities about Al-5Ti-0.62C-1.07La intermediate alloy on the micro-structure together with mechanical features of A356 alloy was studied. The following conclusions were drawn:

(1) Al-5Ti-0.62C-1.07La intermediate alloy could largely purify α-Al dendrites. When the mass fraction of Al-5Ti-0.62C-1.07La intermediate alloy is 6 wt%, the coarse α-Al dendrites change to spherical, together with SDAS declines from 40 μm to 10 μm.
(2) The Al-5Ti-0.62C-1.07La intermediate alloy could sharply ameliorate the eutectic Si composition. When the mass fraction of Al-5Ti-0.62C-1.07La intermediate alloy is 6 wt%, the eutectic Si structure turns from coarse lamellar together with needle-like to short rodlike together with graininess.

(3) As a result of the improvement together with modification about $\alpha$-Al dendrite and eutectic Si crystal, UTS, elongation together with Vickers hardness of A356-T6 alloy are significantly improved, in which UTS, elongation together with Vickers hardness of A356-T6 alloy which is with 6 wt% Al-5Ti-0.62C-1.07La intermediate alloy are increased by 30.3%, 95.2% and 38.1% separately.

Figure 6. SEM imagery and size of eutectic Si in A356-T6 alloy with diverse quantity of Al-5Ti-0.62C-1.07La alloy: (a) unrefined; (b) 4 wt%; (c) 5 wt%; (d) 6 wt%; (e) 7 wt%; (f) size of eutectic Si.
As the increase of Al-5Ti-0.62C-1.07La intermediate alloy content, the fracture formation changes from hypereutectic brittle fracture to ductile fracture.

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Conflicts of interest

There are no conflicts to declare.

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Figure 9. Fractography of the ultimate tensile force specimens of A356-T6 alloy about diverse contents of Al-5Ti-0.62C-1.07La intermediate alloy: (a) unrefined; (b) 4wt%; (c) 5wt%; (d) 6wt%; (e) 7wt%.

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