A new modifier for microstructure and mechanical properties of 6063 aluminum alloy

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Abstract

In this paper, 6063 aluminum alloy for common building profiles is used as the research object. The effect of 6063 aluminum alloy on the microstructure and properties of 6063 aluminum alloy is studied by adding a new type of Al-Ti-C-La master alloy. The results show that Al-Ti-C-La master alloy has an obvious influence on grain refinement of 6063 aluminum alloy. With the addition of Al-Ti-C-La master alloy, the grain size decreased significantly. When the additional amount of Al-Ti-C-La master alloy is 1%, the grain size is reduced from 482 μm to 121 μm. Rare earth La is mainly distributed near the Mg2Si phase and β-AlFeSi, and complex compounds such as AlFeSiMgLa are formed. After aging for 270 days based on T6 heat treatment, the tensile strength, elongation, and Vickers hardness of 6063 aluminum alloy reach 177.2 MPa, 17.8% and 60.9 HV respectively, and the tensile strength is increases by 16.3%. The elongation rate increased by 50.8%, the Vickers hardness decreased by 15.4%, and the ductile fracture was the main fracture of the alloy.

1. Introduction

6063 aluminum alloy is a typical Al-Mg-Si series alloy that can be strengthened by heat treatment. Due to its lightweight, high specific strength, excellent corrosion resistance, easy oxidation coloring, and hot workability, it is widely used in construction and decoration alloy [1–3]. So far, people have continuously strengthened their research on the production requirements and applications of higher standards. Therefore, they have also found that there are still some deficiencies in certain aspects, such as extrusion processability, profile structural steel strength, profile surface color, and decoration, etc [4, 5]. Hence, in order to better improve the actual performance of its production, optimization of its organization and performance is an urgent problem to be solved [6–9].

At present, the research on this problem has been comprehensive, and the most widely used one is to improve the microstructure and properties by adding modifiers or refiners to alloys [10, 11]. British scientist Cibula put forward the carbide boride theory for the first time and thought that the carbide boride theory can significantly improve the refining effect of aluminum alloy [12], which led to the in-depth study of grain refinement of aluminum, Al-Ti-B and Al-Ti-C by later scholars. At present, the application of Al-Ti-B in actual industrial production is relatively mature [13–15], but compared with Al-Ti-C, TiC particles have a smaller aggregation tendency and have the advantage of avoiding poisoning by Zr, Cr, or Mn and other elements [16–18]. However, there are many problems in the preparation process of Al-Ti-C, such as poor wettability between C and aluminum melt, and difficulty in generating TiC by reaction [19, 20].

In view of this, people use the strong surface-active properties of rare earth (RE) and its refining ability to add an appropriate amount of rare earth in the Al-Ti-C to achieve the purpose of grain refinement. Xu Chunxiang
2. Experimental materials and methods

The main experimental material is 6063 aluminum alloy and the self-made Al-Ti-C-La master alloy made by the research group based on previous research. The chemical composition of 6063 aluminum alloy used in this experiment is shown in table 1. Firstly, 6063 aluminum alloy is put into the graphite crucible, and then it is heated to 730 °C for 10 min, and then the reheat preservation for 10 min, and then the removal. When the melt temperature is kept at 730 °C, the alloy sample can be prepared by adding the self-made Al-Ti-C-La master alloy in the early stage and applied it to pure aluminum [23]. The result shows that the addition of RE elements can boost the wettability between C and aluminum melt, promote the synthesis of TiC, and inhibit the aggregation and deposition of the second phase particles in the intermediate alloy in the refining process, which is conducive to improving the performance of the alloy.

Therefore, this paper attempts to add a self-made new Al-Ti-C-La master alloy to 6063 aluminum alloy, research the refinement effect of Al-Ti-C-La master alloy on 6063 aluminum alloy. Discuss the existence form, distribution state of RE La in 6063 aluminum alloy and its effect and mechanism of action on the second phase particles, and its influence on the hardness, tensile properties, and fracture morphology of 6063 aluminum alloy is analyzed, in order to provide theoretical and technical guidance for the practical application of Al-Ti-C-La master alloy in 6063 aluminum alloy.

Table 1. Chemical compositions of 6063 Aluminum alloy (wt.%).

| Chemical element | Si  | Fe  | Cu  | Zn  | Mg  | Al  |
|------------------|-----|-----|-----|-----|-----|-----|
| Content          | 0.41| 0.14| 0.04| 0.02| 0.57| Bal.|

Table 2. The sample number of Al-Ti-C-La master alloy refined 6063 aluminum alloy.

| Alloy number | Alloy composition |
|--------------|-------------------|
| #1           | 6063              |
| #2           | 6063 + 0.2% Al-Ti-C-La |
| #3           | 6063 + 0.5% Al-Ti-C-La |
| #4           | 6063 + 1.0% Al-Ti-C-La |

[21] et al studied the influence of La on the structure and refinement performance of Al-Ti-C. The results showed that the addition of La would make the distribution of Al3Ti and TiC particles in the matrix more dispersed and obtained excellent grain refinement performance for commercially available pure aluminum. Zhang Jianxin [22] et al found that the proper amount of Ce can enhance the heat treatment effect of Al-Ti-C on Al-Mg-Si alloy, and improve the strength and elongation of the alloy. The research team prepared Al-Ti-C-La master alloy in the early stage and applied it to pure aluminum [23]. The result shows that the addition of RE elements can boost the wettability between C and aluminum melt, promote the synthesis of TiC, and inhibit the aggregation and deposition of the second phase particles in the intermediate alloy in the refining process, which is conducive to improving the performance of the alloy.

Therefore, this paper attempts to add a self-made new Al-Ti-C-La master alloy to 6063 aluminum alloy, research the refinement effect of Al-Ti-C-La master alloy on 6063 aluminum alloy. Discuss the existence form, distribution state of RE La in 6063 aluminum alloy and its effect and mechanism of action on the second phase particles, and its influence on the hardness, tensile properties, and fracture morphology of 6063 aluminum alloy is analyzed, in order to provide theoretical and technical guidance for the practical application of Al-Ti-C-La master alloy in 6063 aluminum alloy.
and water quenching is carried out. The aging treatment temperature is 200 °C, the temperature is kept for 2 h, and then air cooling is carried out. On this basis, the morphological changes of the alloy before and after heat treatment are analyzed. The mechanical properties of the alloy were characterized after natural aging for 270 days on the basis of T6.

3. Results and discussion

3.1. Microstructure of Al-Ti-C-La master alloy

The microstructure characteristics of Al-Ti-C-La master alloy determine its refining effect. As shown in figure 1(a), the phase in the Al-Ti-C-La master alloy is mainly composed of the rare earth phases Ti2Al20La, Al3Ti phase and TiC particles except for the α-Al matrix. The rare earth phase Ti2Al20La is a bright white polygonal block and is wrapped with Al3Ti. As shown in figure 1(b), TiC is mainly distributed in the form of granular agglomerations, with sizes ranging from 0.1 μm to 1.2 μm.

In order to analyze the action mechanism of Al-Ti-C-La master alloy, it is necessary to study the existing form and microstructure of TiC particles. The TiC particles in the Al-Ti-C-La master alloy were analyzed by TEM. Figure 2 shows the open field phase of TiC particles with the particle size of about 0.2 μm, which is evenly distributed without segregation. There are (001)Al//[011]TiC and [001]Al//[011]TiC orientations between TiC and Al, and both TiC and Al are face centered cubic structures with very similar lattice constants (aTiC = 0.432 nm, aAl = 0.404 nm). Moreover, TiC has a high melting point (3147 °C) and is very stable [24]. Therefore, it may be an ideal crystal nucleus for aluminum crystallization and contribute to grain refinement of 6063 aluminum alloy.

3.2. Effect of Al-Ti-C-La master alloy on the microstructure of 6063 aluminum alloy

Figure 3 shows the macro morphology of Al-Ti-C-La master alloy added to 6063 aluminum alloy. It can be seen from figure 3(a) that the macrostructure grain of #1 sample is coarse, the center is composed of equiaxed crystal and the edge is composed of columnar crystal. Compared with figures 3(a)–(d), it is found that Al-Ti-C-La master alloy has an obvious improvement effect on the structure of 6063 aluminum alloy. It can be looked from figure 3(b) that the size of coarse equiaxed crystal and edge columnar crystal in the center of #2 sample decreased obviously and some fine equiaxed crystal replaced the edge columnar crystal. The grain refinement effect of #3 sample is very obvious. The coarse and uneven equiaxed crystal in the center is refined into a fine equiaxed crystal, and the columnar crystal with a long strip at the edge has vanished and substituted by a fine and equiaxed crystal. When the addition amount of Al-Ti-C-La master alloy continues to increase, the grain size is further reduced and the structure distribution is more uniform, as shown in figure 3(d).

Figure 4 shows the microstructure of 6063 aluminum alloy with different content of Al-Ti-C-La master alloy. It can be seen from the figure that adding Al-Ti-C-La master alloy to 6063 aluminum alloy has better grain refinement effect than #1 without master alloy. #1 sample is composed of α-Al grains and eutectic structure continuously distributed at the grain boundary α-Al grains show a rough and uneven distribution of dendrites and petals, as shown in figure 4(a). The grain size of #2 sample is finer than that of #1 sample, and the
precipitation amount at the grain boundary is increased, as shown in figure 4(b). The grains of #3 sample and #4 sample is significantly refined, and coarse dendrite grains are refined into equiaxed grains. As the number of grain boundaries increases, part of the second phase precipitates in the grains. With the increase of the content of Al-Ti-C-La master alloy, the number of the second phase also increases gradually, as shown in figures 4(c) and (d).

Figure 5 is the bar chart of the average grain size of 6063 aluminum alloy with different content of Al-Ti-C-La master alloy. It can be seen that the average grain size of α-Al gradually decreases with the increase of the addition amount of Al-Ti-C-La master alloy. When 0%, 0.2%, 0.5% Al-Ti-C-La master alloy is added to 6063 aluminum alloy, the average grain size of α-Al is 482 μm, 234 μm, and 168 μm respectively. When the addition of Al-Ti-C-La master alloy is 1%, the average grain size of 6063 aluminum alloy is refined to 121 μm, which is 74.8% higher than that of 0%.

Generally speaking, there are two kinds of precipitates in the structure of 6063 aluminum alloy, one is coarse and irregular strip or dendritic β-AlFeSi phase, and most of these precipitates exist at grain boundaries; The other is short rod or granular Mg2Si phase, which mostly exists in grains, but a small amount exists at grain boundaries. However, the Mg2Si phase plays a main role in dispersion strengthening, which can also reduce stress concentration. Further study on the morphology and distribution of the second phase in 6063 aluminum alloy after adding Al-Ti-C-La master alloy can provide experimental evidence for analyzing the refinement mechanism and performance strengthening mechanism of Al-Ti-C-La master alloy on 6063 aluminum alloy.

Figure 6 shows the morphology of precipitates in #4 sample. It can be observed that the precipitates in the alloy have three different morphologies: long strip, agglomerated large particle and dispersed small particle. It can be seen from the energy spectrum analysis results of the precipitates that the precipitates in the long strip shape of the crystal boundary in figure 6(a) are rich in Al, Fe, and Si elements, which are considered as β-AlFeSi phase by analysis; From figure 6(b), it can be seen that some large particle precipitates contain Mg and La elements besides Al, Fe, Si, and other elements, which are considered as AlFeSiMgLa compounds by analysis; As can be seen from figure 6(c), some small particulate precipitates contain Al, Si, and Mg element, and the ratio of Mg and Si is close to 2:1, which is considered to be the Mg2Si phase.

Figure 7 shows the morphology of precipitated phases in the samples of #1 and #4 after heat treatment, and the results of energy spectrum calibration are shown in the figure. It can be seen from figure 7 that there are the bright white round MgSi phase and the elongated β-AlFeSi phase in #1 sample after heat treatment, while AlFeSiMgLa compound is added in #4 sample due to the addition of Al-Ti-C-La. Comparing the precipitated phases in #4 sample and #1 sample, it can be seen that after adding Al-Ti-C-La, the MgSi phase of large particles becomes fine, and the distribution of β-AlFeSi phase becomes more uniform, which mostly appears at the grain boundary. However, compared with figure 6, the morphology and distribution of precipitates in #4 sample after heat treatment have no obvious change.

Figure 8(a) shows the particles A inside the grains of #4 sample and their EDS analysis diagrams. It can be seen that the grains of α-Al contain small white particles with a size of about 3 μm. The composition detection by
EDS energy spectrum shows that the main composition of the particles is divided into Al, C and Ti, which can be judged as TiC. As the TiC particles in Al-Ti-C-La master alloy are relatively small, the results show that there is Al element in the particles.

In order to further explore the mechanism of RE La in the refining process of 6063 aluminum alloy, the distribution of RE La in 6063 aluminum alloy was analyzed by EPMA surface scanning spectrogram. Figure 9 is the EPMA surface scanning spectrum of #1 sample. It can be seen that the distribution form of Fe is long strips and dendrites, and concentrated in the grain boundary of $\alpha$-Al. The distribution of Si is very similar to that of Fe, which is concentrated in $\alpha$-Al grain boundary in long strips and dendrites, and a small amount of Si is also present in the crystal.

Figure 10 is a surface scanning spectrogram of EPMA of #4 sample. It can be seen that Fe and Si are distributed in the $\alpha$-Al grain boundary in a spherical or short rod shape, while Mg is more dispersed in the aluminum matrix than in figure 9(e). It can be seen from figure 10(f) that the rare earth La is mainly distributed in the areas where Si and Fe are enriched. In 6063 aluminum alloy, on the one hand, the Mg element plays the role of solution strengthening when it is dissolved in $\alpha$-Al, on the other hand, Mg and Si react in aluminum solution to form the strengthening phase Mg$_2$Si. Therefore, it can be concluded that La is mainly distributed near the Mg$_2$Si phase and $\beta$-AlFeSi phase in 6063 aluminum alloy.

Based on the above analysis, the influence of Al-Ti-C-La master alloy on the grain refinement and microstructure of 6063 aluminum alloy is mainly due to the face-centered cubic structure of $\alpha$-Al and TiC, in which the lattice constant of $\alpha$-Al($a_{\text{Al}}$) is 0.404 nm and that of TiC($a_{\text{TiC}}$) is 0.432 nm. Therefore, the lattice mismatch $\delta$ between $\alpha$-Al and TiC is 6.9%, less than 25% and, greater than 5%, that is, there is a partially coherent interface between the TiC substrate and $\alpha$-Al matrix, which makes the TiC particles contained in the
Al-Ti-C-La master alloy can be used as the heterogeneous nucleation core of $\alpha$-Al [18, 25]. Theoretically, the more the amount of master alloy is added, the more TiC particles it contains, and the better the refining effect; Besides, the RE phases Ti$_2$Al$_2$O$_3$La and Al$_4$Ti included in Al-Ti-C-La master alloy can not exist stably in the aluminum melt, and they will decompose, and the Ti and La atoms produced by decomposition will be enriched on the surface of TiC particles, forming the enrichment layer of Ti and La atoms. The enrichment layer can not only prevent TiC from poisoning due to the formation of Al$_4$C$_3$, but also cause constitutional supercooling, which hinders the grain growth during solidification and plays a refining role [23, 26].

Figure 4. Optical micrograph images of 6063 aluminum alloy using the different content Al-Ti-C-La master alloy: (a) #1 sample; (b) #2 sample; (c) #3 sample; (d) #4 sample.

Figure 5. Bar charts of the average grain size of 6063 aluminum alloy using the different content Al-Ti-C-La master alloy.
Finally, some rare earth La produced by decomposition will be adsorbed on the surface of Mg$_2$Si phase and β-AlFeSi phase. Because La is a surfactant, it can inhibit the growth of Mg$_2$Si phase and β-AlFeSi phase, and it can improve their morphology and distribution. Also, some scholars [27] believe that the temperature range of some alloy phases is changed because the RE La is easily accumulated on the front edge of the solid-liquid interface when 6063 aluminum alloy is added with a small amount of RE La. On the one hand, it leads to lower solidification temperature, faster growth speed, and smaller dendrite spacing. On the other hand, in the process of dendrite growth, the solute at the front of the solid-liquid interface is redistributed, which leads to the increase of the constitutional supercooling area, the increase of crystal cores, and the decrease of dendrite spacing.

3.3. Effect of Al-Ti-C-La master alloy on mechanical properties and fracture morphology of 6063 aluminum alloy

3.3.1. Effect on mechanical properties

After 270 days of natural aging based on T6 treatment, the comparison of the ultimate tensile strength (UTS), elongation, and hardness of 6063 aluminum alloy is shown in figure 11. From figure 11(a), it can be observed that the tensile strength of 6063 aluminum alloy of #1 sample is 152.4 MPa and the elongation is 11.8%. With the increase of the content of Al-Ti-C-La master alloy, the tensile strength and elongation of 6063 aluminum alloy are enhanced significantly. Among them, #4 sample has the most obvious improvement, its tensile strength has increased by 16.3%, and its elongation has increased by 50.8%. It can be seen from figure 11(b) that with the increase of the content of Al-Ti-C-La master alloy, the Vickers hardness of #1 sample, #2 sample, #3 sample, and #4 sample is 72.0 HV, 67.9 HV, 67.6 HV, and 60.9 HV respectively and the Vickers hardness of #4 sample is 15.4% lower than that of #1 sample.

Figure 6. Precipitates at the crystal boundary of #4 sample: (a) long strip of β-AlFeSi; (b) large particles of AlFeSiMgLa; (c) small particles of Mg$_2$Si.
From the data analysis, it can be concluded that adding different content of Al-Ti-C-La master alloy to 6063 aluminum alloy can enhance the mechanical properties of the alloy, mainly because adding Al-Ti-C-La master alloy can effectively refine the \( \alpha \)-Al grains. The smaller the grain size, the more the grain boundary, the higher the metal strength. The effect of grain size on the mechanical properties of metals can generally be described by Hall-Petch [28], as shown in formula (1):

\[
\sigma_s = \sigma_0 + k d^{-1/2}
\]
\(\sigma_s\) is the yield strength of the material, \(d\) is the grain size, and \(\sigma_0\) and \(k\) are constants related to the material. From the formula, it can be seen that smaller grain sizes will have higher yield strength. The essence of fine grain strengthening lies in the barrier effect of grain boundary on dislocation. The smaller the grain size, the more the grain boundaries, the greater the blocking effect, and the better the strengthening effect. Grain boundaries are also the obstacle of crack growth, so grain refinement can improve the toughness of alloy. For another, after the addition of Al-Ti-C-La master alloy, the original coarse \(\beta\)-AlFeSi phase in the alloy changes into a small particles and short rod, which reduces the cleavage effect on the alloy matrix and enhances the performance of the alloy.

Figure 9. EPMA analysis of \#1 sample: (a) back-scattered electron image; (b–e) X-ray image of elements Al, Fe, Si and Mg.
However, RE La will produce complex compounds with Fe, Si and other elements. The formation of these complex compounds consumes Si and Mg elements, resulting in a reduction in the number of strengthening phase Mg$_2$Si, which may lead to a decrease in the hardness of the alloy. At the same time, the addition of excessive Al-Ti-C-La master alloy will obviously affect the amount of strengthening phase Mg$_2$Si, which will result in a significant decrease in Vickers hardness of the alloy. Therefore, when the addition amount of Al-Ti-C-La master alloy is 0.2%, the tensile strength and elongation of 6063 aluminum alloy can be obviously increased, while the Vickers hardness reduces slightly.

Figure 10. EPMA analysis of #4 sample: (a) Backscattered electron images; (b–f) x-ray images of Al, Fe, Si, Mg, and La elements.
3.3.2. Effect on fracture morphology

Figure 12 shows the tensile fracture morphology of the alloy at room temperature. As can be seen from figure 12 that the necking phenomenon occurs during the fracture of the alloy. The macro fracture of the sample is cup-shaped and the crack source is generated on the surface of the sample. The alloy is a mainly ductile fracture, and there are also ductile fracture and brittle mixed fracture. Figure 12(a) is #1 sample without master alloy. It can be
seen that there are a large number of $\beta$-AlFeSi phases and a certain amount of dimples at the crack source. This shows that due to the segregation of large-size $\beta$-AlFeSi and other complex compounds at the grain boundary, cracks are produced and intergranular fracture occurs in the $\#1$ sample. It can be seen from figure 12(b) that there are also a large number of $\beta$-AlFeSi phases and dimples at the crack source of $\#2$ sample, but compared with $\#1$ sample, both the AlFeSi phase and dimples are reduced, indicating that the plasticity of the $\#2$ sample is better than that of $\#1$ sample. From figure 12(c), it can be seen that there are fewer dimples and shallow $\beta$-AlFeSi on the fracture surface of $\#3$ sample, indicating that the plasticity of $\#3$ sample is better than that of $\#1$ sample and $\#2$ sample. Compared with other alloys, $\#4$ sample has more and finer dimples on the fracture surface, with the highest plasticity.

4. Conclusion

(1) Al-Ti-C-La master alloy has a better grain refinement effect on 6063 aluminum alloy. With the increase of Al-Ti-C-La master alloy, the microstructure is mainly composed of fine and uniform equiaxed grains, and the grain size decreases significantly. When the addition amount of Al-Ti-C-La master alloy is 1%, the average grain size is reduced from 482 $\mu$m to 121 $\mu$m.

(2) Based on the addition of 1% Al-Ti-C-La master alloy, it is found that there are not only long $\beta$-AlFeSi phase and granular Mg$_2$Si phase, but also some large granular AlFeSiMgLa compounds. At the same time, there are small white particles TiC in the grains, which can be used as the heterogeneous nucleation core of $\alpha$-Al. Besides, there will be enriched layers of Ti and La atoms on the surface, which play a refining role.

(3) Rare earth La will be adsorbed on the surface of Mg$_2$Si phase and $\beta$-AlFeSi phase, which can inhibit the growth of Mg$_2$Si phase and $\beta$-AlFeSi phase, improve their morphology and distribution, and improve their structure and performance.

(4) After 270 days of natural aging based on T6 heat treatment, the tensile strength and elongation of 6063 aluminum alloy increase with the increase of the amount of intermediate alloy, and the hardness decreases gradually. With the addition of 1% Al-Ti-C-La master alloy, the tensile strength and elongation of 6063 aluminum alloy increase the most, and there are more small dimples on the fracture surface. The fracture mode of the alloy is a mainly ductile fracture.

Author Contributions

Wanwu Ding and Xiaoxiong Liu conceived and designed the experiments; Xiaoxiong Liu, Xiaoyan Zhao and Taili Chen carried out the experiments and data collection; Wanwu Ding, Xiaoxiong Liu, Haixia Zhang, Wenjun Zhao, and Changfeng Li analyzed the data; Wanwu Ding contributed reagents/materials/analysis tools; Xiaoxiong Liu wrote the paper. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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References

[1] Wu X Y, Yun Y, Zhang H R, Ma Z, Jia L N, Tao T X and Zhang H 2017 Effect of holding pressure on microstructure and fracturebehavior of low-pressure die cast A356-T6 alloy Mater. Res. Express 4 126501–10

[2] Panigrahi S K, Jayaganthan R and Pancholi V 2009 Effect of plastic deformation conditions on microstructural characteristics and mechanical properties of Al 6063 alloy Mater. Des. 30 1894–901
[3] Ruan Y, Qiu X M and Gong W B 2012 Mechanical properties and microstructures of 6082-T6 joint welded by twin wire metal inert gas arc welding with the SiO₂ flux Mater. Des. 35 20–4
[4] Camero S, Puchi E S and González G 2006 Effect of 0.1% vanadium addition on precipitation behavior and mechanical properties of Al-6063 commercial alloy J. Mater. Sci. 41 7361–73
[5] Lin Y C, Luo S C and Huang J 2018 Effects of solution treatment on microstructures and micro-hardness of a Sr-modified Al-Si-Mg alloy Mater. Sci. Eng. A 725 530–40
[6] Karakoc H, Karabulut S and Citak R 2018 Study on mechanical and ballistic performances of boron carbide reinforced Al 6061 aluminum alloy produced by powder metallurgy Compos. Part. B-Eng 148 68–80
[7] Wang E, Gao T and Nie J 2014 Grain refinement limit and mechanical properties of 6063 alloy inoculated by Al-Ti-C (B) master alloys J. Alloys Compd. 594 7–11
[8] Thanapandian N, Balasivanandha P S and Padmanabhan K A 2019 Effect of temperature on grain size in AA6063 aluminum alloy subjected to repetitive corrugation and straightening Acta. Metall. Sin. 74 45–98
[9] Camero S, Puchi E S and González G 2006 Effect of 0.1% vanadium addition on precipitation behavior and mechanical properties of Al-6063 commercial alloy J. Mater. Sci. 41 7361–73
[10] Liu R, Yao J H and Zhang Q L 2015 Relations of chemical composition to solidification behavior and associated microstructure of stellite alloys Metalloge. Microstruct. Anal. 62 146–57
[11] Ding W W, Zhao W J and Xia T D 2014 Grain refining action of Al-5Ti-C and Al-TiC master alloys with Al-5Ti master alloy addition for commercial purity aluminum Int. J. Cast Met. Res. 27 187–92
[12] Cibula A 1951 The grain refinement of aluminum alloy castings by additions of titanium and boron J. Inst. Metals. 80 15–94
[13] Li P T, Liu S D, Zhang L L and Liu X F 2013 Grain refinement of A356 alloy by Al-Ti-B-C master alloy and its effect on mechanical properties Mater. Des. 47 522–8
[14] Kori S A and Auradi V 2007 Influence of reaction temperature for the manufacturing of Al-3Ti and Al-3B master alloys and their grain refining efficiency on a Al-7Si5 alloy Adv. Mater. Res. 30 111–5
[15] Sun J Y, Li C, Liu X F, Yu L M, Li H J and Liu Y C 2017 Investigation on AlIP as the heterogeneous nucleus of Mg₂Si in Al-Mg₂Si alloys by experimental observation and first-principles calculation Results. Phys. 8 146–52
[16] Carver R F, Boone C W and Koch F P 1990 Characteristics of new generation grain refiners Light. Metals. 67 845–50
[17] Mayes C D, Mc Cartney D G and Tatlock G J 1994 Observations on the microstructure and performance of an Al-Ti-C grain-refining master alloy Mater. Sci. Eng. A 188 283–90
[18] Ding W W, Chen T L and Zhao X Y 2020 Investigation of microstructure of Al-5TiC-0 62C system and synthesis mechanism of TiC Mater. Des. 151 1–13
[19] Zhao H L, Guan R G and Li M 2014 Microstructure and phase forming process of Al-3Ti-C-0 2C-1RE grain refiner J. Cent. South. Univ. 21 1–8
[20] Rao A K P, Das K, Murty B S and Chakraborty M 2009 Al-Ti-C-Sr master alloy-amelt inoculant for simultaneous grain refinement and modification of hypoeutectic Al-Si alloys J. Alloys Compd. 480 25–973
[21] Xu C X, Liang L P, Li B F, Zhang J and Liang W 2006 Effect of La on microstructure and grain-refining performance of Al-Ti-C grain refiner J. Rare. Earth. 24 596–601
[22] Zhang J X and Gao A H 2007 Analysis of factors affecting the refinement effect of Al-Ti-C on aluminum alloys Foundry. Tech. 28 680–2
[23] Ding W W, Xu C and Hou X G 2018 Preparation and synthesis thermokinetics of novel Al-Ti-C-La master alloys J. Alloys Compd. 736 1–11
[24] Zhang B Q, Li J G and Ma H T 2000 New development of Al-Ti-C grain refining master alloys Trans. Nonferr. Met. Soc. China. 10 298–303
[25] Patankar U, Kajorchnayakul J and Limmaneevichit C 2012 Grain refinement mechanism in an Al-Si-Mg alloy with scandium J. Alloys Compd. 542 177–86
[26] Kennedy A R, Weston D P and Jones M I 2000 Reaction in Al-Ti-C powders and its relation to the formation and stability of TiC in Al at high temperatures Scripta. Mater. 42 1187–92
[27] Yang T E, Xiong J, Yang Q P and Xu H Y 2016 Study on microstructure and aging properties of rare earth La modified 6063 aluminum alloy Hot Processing Technology. 45 29–33
[28] Ma K, Wen H, Hu T, Topping T D, Isheim D and Seidman D N 2014 Mechanical behavior and strengthening mechanisms in ultrafine grain precipitation-strengthened aluminum alloy Acta Mater. 62 141–55