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Effect of Ti on microstructure and properties of electromagnetic stirred Al-18wt.%Mg_2Si alloy

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Abstract: By adding different amounts of Ti into the electromagnetic stirred Al-18wt.%Mg_2Si alloy, the effect of Ti element on the microstructure and mechanical properties of the alloy was studied. The experimental results show that the microstructure is refined after modification with Ti, which is related to the heterogeneous nucleation of $TiAl_3$ particles on the α-Al matrix. With the increase of Ti content and holding time after stirring, the primary Mg_2Si phase is refined firstly and then coarsened, and correspondingly, the mechanical properties of the alloy show a trend of increasing at first and then decreasing. When the addition of Ti is 0.5wt.% and the holding time is about 20 min, the refinement effect of primary Mg_2Si phase is the most significant and the mechanical properties of the alloy are optimal.

Keywords: Al-18wt.%Mg_2Si alloy; Ti modification; electromagnetic stirring; mechanical property

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1 Introduction

With the rapid development of aerospace and automobile industries, problems such as the energy shortage and environmental pollution have become increasingly serious. Therefore, more attentions are paid to the research and development of weight reduction and energy saving technology. The intermetallic compound Mg_2Si has advantages such as low density, high melting temperature and high specific strength, and thus can be used as a high temperature structural material [1]. The Al-Mg_2Si composite can be obtained by casting process with low cost, and it has very good compatibility and excellent thermal stability. However, the Mg_2Si phase in the Al-Mg_2Si composite is usually very coarse and mostly spear-like shaped, which fragmentates the matrix and leads to a decrease in mechanical properties [2].

Among the grain refining elements for aluminum alloy [3-6], Ti has a relatively high grain growth restrained effect, which can be used as an effective nucleation agent. The microstructure of Al alloy can be significantly refined by adding a small amount of Ti, thereby improving the mechanical properties of the alloy, e.g., strength, toughness, wear resistance, anti-fatigue properties and thermal fatigue property. By means of thermal analysis, directional solidification and metallographic technique, the effects of Li and Ti on the pseudobinary eutectic reaction L<=>α(Al)+Mg_2Si and the phase constitution of Al-Mg_2Si pseudobinary eutectic composite in the ternary Al-Mg-Si system was studied by Zhao et al.[7, 8], and the results show that the volume fraction of the strengthening phase Mg_2Si in the composite is affected by the type of added elements. The addition of Li will reduce the volume fraction of Mg_2Si in the alloy, while the addition of a little amount of Ti will increase the volume fraction of Mg_2Si. Wu et al. [9] found that the low superheat + electromagnetic stirring (EMS) process can refine the grain structure of primary α-Al and α-Al+Mg_2Si eutectic cell, as well as the eutectic Mg_2Si phase, which promotes the formation of non-dendritic phases and changes the nucleation mode of α-Al+Mg_2Si binary eutectic from the nucleation on primary α-Al under conventional casting to the one on nuclei in the interdendritic liquid under low superheat + EMS. It shows obviously that alloying element modification and EMS are effective ways to change the microstructure of Al+Mg_2Si alloy.

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In the previous research works, the influence of electromagnetic stirring on the structure and properties of Al-18wt.%Mg_2Si alloy was studied. Results showed that electromagnetic stirring can refine the structure and therefore improve the performance of Al-18wt.%Mg_2Si alloy, and the optimal properties can be obtained under electromagnetic induction intensity of 0.1 T and stirring time of 1 min [10]. In this study, Al-18wt.%Mg_2Si alloys with different addition amounts of Ti were prepared under the optimal electromagnetic stirring parameters (0.1 T for 1 min) based on Ref. [10] with different holding times, and the effects of Ti content, as well as the holding time after stirring on the microstructure and mechanical properties of the alloy were evaluated.

2 Experimental procedure

Industrial pure Al, Mg and Al-20Si master alloy were used as raw materials, and they were melted in a graphite crucible in a high temperature electric resistance furnace. The modification element Ti (0.1wt.%, 0.3wt.%, 0.5wt.% and 0.9wt.%, respectively) was added into the melt using Al-5wt.%Ti master alloy, and then the melt was refined and degassed with C_2Cl_6. After the melt being held for 3–5 min at 750 °C, the slag was removed. The graphite crucible containing the melt was put into an electromagnetic stirring device, where the melt was stirred for 1 min at a magnetic induction intensity of 0.1 T. After stirring, the melt held for different times (10, 20 and 30 min, respectively) and was then poured into a steel mold preheated to 200 °C to obtain the cast ingots weighing about 0.8 kg, as shown in Fig. 1.

The tensile specimens, as shown in Fig. 2, were cut from the middle of the ingot to perform the mechanical property tests.

In addition, some cylindrical specimens were also cut from the middle of the ingot for microstructure analysis and hardness tests. The microstructure of the specimens was examined using an optical microscope (OM) and a scanning electron microscope (SEM), respectively. The hardness was measured using a HB-3000 Brinell hardness tester. The tensile properties of the test specimens were investigated with a WES hydraulic universal tester.

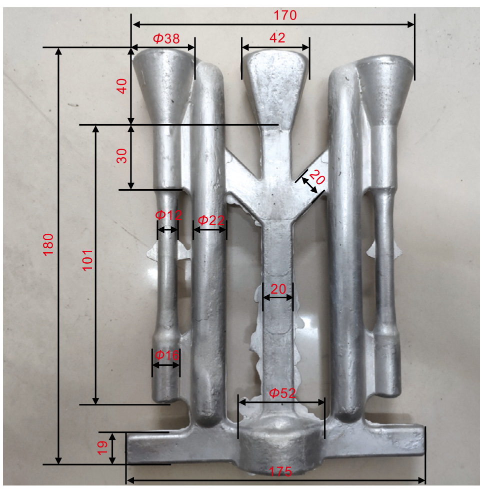


Fig. 1: Casting ingot (Unit: mm)

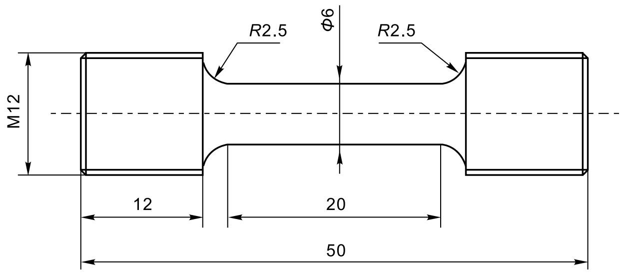


Fig. 2: Dimensions of tensile specimen (Unit: mm)

3 Results and discussion

3.1 Influence of Ti content on microstructure

Figure 3 shows the influence of Ti content on the microstructure of the electromagnetic stirred Al-18wt.%Mg_2Si alloy with the holding time of 20 min, in which the black block structure is the primary Mg_2Si phase. Compared with the alloy without Ti addition, the microstructure of the alloy containing 0.1wt.% Ti changes slightly, showing a reduced segregation effect of the primary Mg_2Si phase. The primary phase in the two alloys is relatively coarse and oval, and shows an obvious intermittent dendrite segregation phenomenon. When the addition of Ti is 0.3wt.% and 0.5wt.%, the primary phase in the alloys is obviously refined. The Mg_2Si grains in the alloy with 0.5wt.% Ti content have a minimum size and a more uniform distribution, and the segregation phenomenon is basically eliminated. The further increase Ti content (0.9wt.%), however, will significantly coarsen the primary phase, resulting in the Mg_2Si grains in the shape of multangular block or strip with prominent angles, which can be found from the alloy with 0.9wt.% Ti as shown in Fig. 3(e).

The typical microstructures of Ti modified Al-18wt.%Mg_2Si alloy (Ti is 0.9wt.%) including primary Mg_2Si, eutectic Al+Mg_2Si and α-Al matrix are shown in Fig. 4. According to the EDS measured results, the structure of Area (A) is eutectic Al+Mg_2Si structure and Area (B) is the primary Mg_2Si phase. Area (C) in Fig. 4 shows the enlarged Al+Mg_2Si structure of the Al-18wt.%Mg_2Si-0.9wt.%Ti alloy, and it is clearly that the eutectic Mg_2Si is in the form of short fiber or sphere.

3.2 Influence of holding time on microstructure

During the melting process, the holding time after stirring has a remarkable influence on the modification effect of Ti, as shown in Fig. 5, which is exemplified by the microstructure of Al-18Mg_2Si alloy with the Ti content of 0.5%. Figure 5(a) shows the microstructure of the alloy subjected with electromagnetic stirring followed by holding for 10 min. Compared to the grain size of primary Mg_2Si in the alloy without Ti [Fig. 3(a)], the refining effect is not obvious. When the holding time is extended to 20 min, the primary phase becomes finer and distributes more evenly on the Al matrix, while the degree of segregation reduces, as shown in Fig. 5(b). When the holding time is extended to 30 min, as shown in Fig. 5(c), the primary Mg_2Si phase, however, becomes larger in size again and tends to be more round, whose morphology and distribution are similar to the alloy without Ti addition.

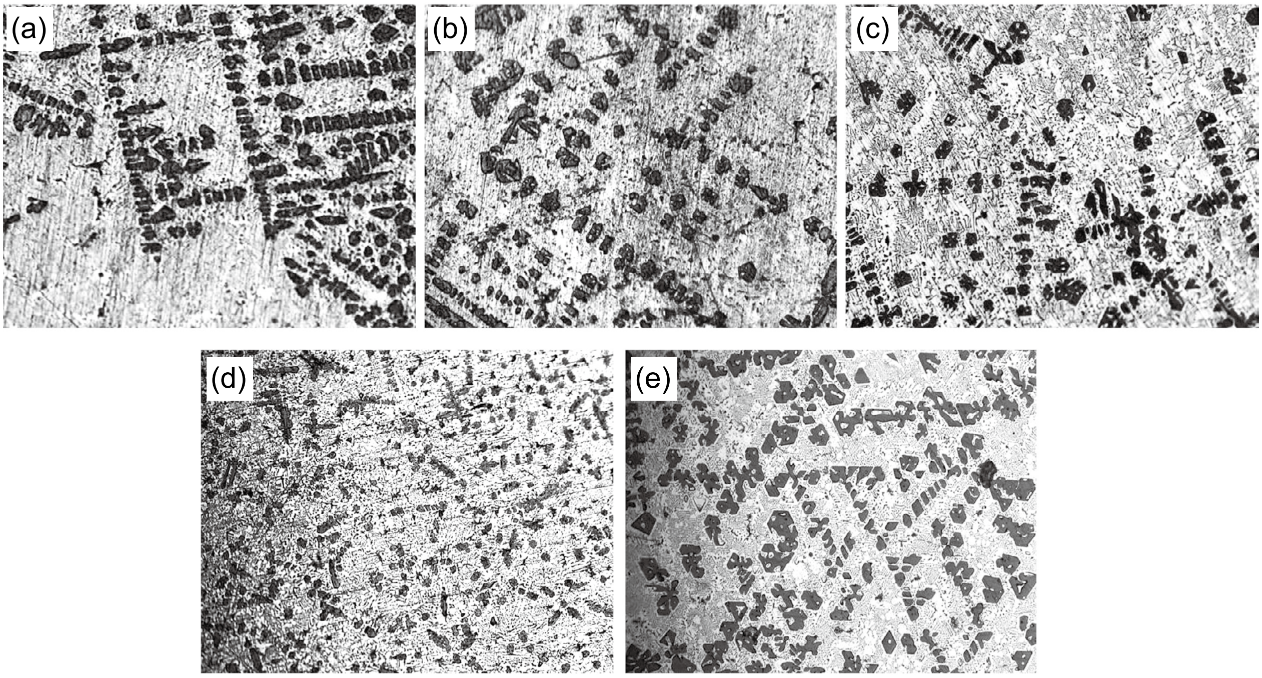


Fig. 3: Microstructures of Al-18wt.%Mg_2Si alloys with Ti content of 0 (a), 0.1wt.% (b), 0.3wt.% (c), 0.5wt.% (d) and 0.9wt.% (e), respectively

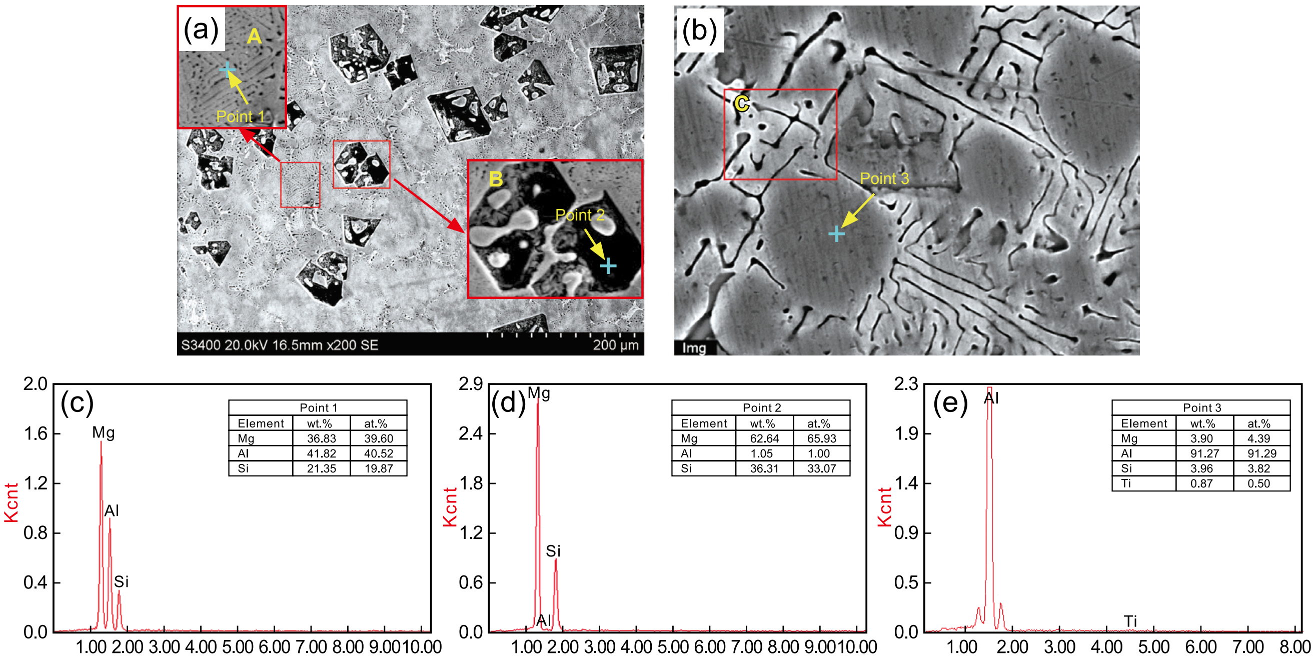


Fig. 4: Typical microstructures (a-b) and EDS measured results (c-e) of Al-18wt.%Mg_2Si-0.9wt.%Ti alloy

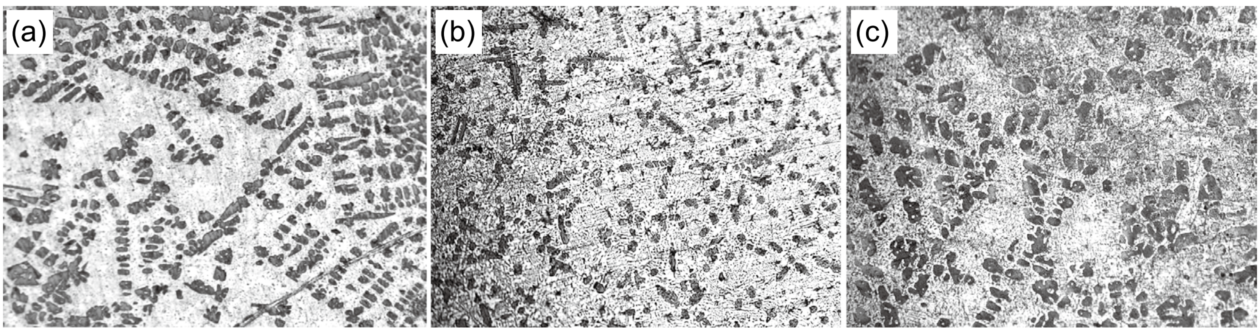


Fig. 5: Microstructures of electromagnetic stirred Al-18wt.%Mg_2Si-0.5wt.%Ti alloys that subjected with holding time of 10 min (a), 20 min (b), and 30 min (c)

3.3 Influence of Ti modification on mechanical properties

Figure 6 shows the mechanical properties of the electromagnetic stirred Al-18wt.%Mg_2Si-*x*wt.%Ti alloys subjected to the holding time of 20 min. It can be found the mechanical properties of the alloys, including hardness, elongation and tensile strength, show a trend of increase at first and then decrease with the increase of Ti addition amount. The testing results in Fig. 6 indicate that the tensile strength, elongation and hardness of the alloy increases rapidly and reaches the peak values when the Ti addition is increased from 0 to 0.5wt.%, suggesting that the Al-Mg_2Si alloy with 0.5wt.%Ti has the optimal overall mechanical properties. The tensile strength, elongation and hardness of the Al-18wt.%Mg_2Si-0.5wt.%Ti are 231 MPa, 2.68% and 65 HB, respectively, which are 13.8%, 13.6% and 16.1% higher than the alloy without Ti addition. As the Ti content continues to increase, the mechanical properties of the alloy decrease. The experimental results show that the variation trend of mechanical properties of the Al-18wt.%Mg_2Si-*x*wt.%Ti alloys follows the variation trend of the microstructure, i.e., the refinement degree of the primary Mg_2Si particles has a significant influence on the mechanical properties of the alloys.

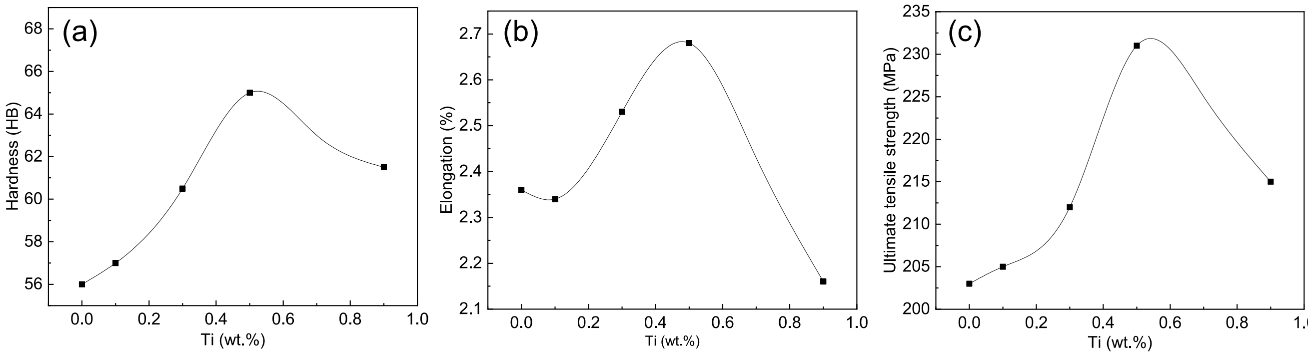


Fig. 6: Curves of hardness (a), elongation (b), and ultimate tensile strength (c) of Al-18wt.%Mg_2Si alloy with different Ti contents

3.4 Discussion

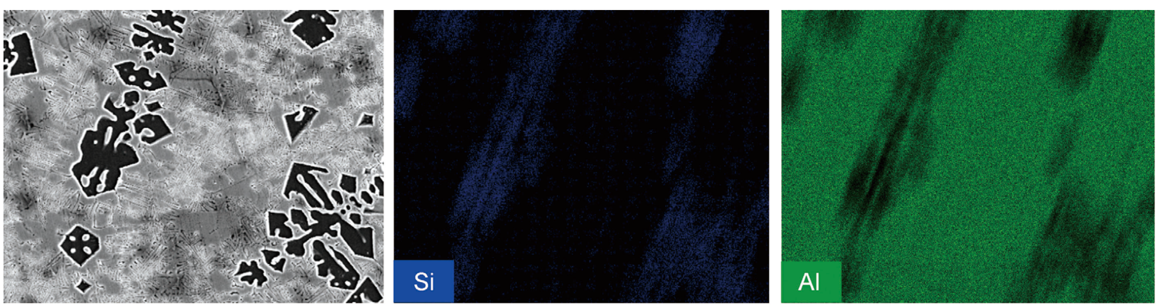
The above experimental results show that Ti element has a significant refining effect on the electromagnetic stirred Al-Mg_2Si alloy. The corresponding action mechanism is as follows.

According to the equilibrium pseudo binary Al-Mg_2Si phase diagram [11, 12], when the mass fraction of Mg_2Si is ranging between 13.9% and 25%, the pseudo-hypereutectic reaction can be expressed as:

$$L \rightarrow (Mg_2Si)_P + L_1 \rightarrow (Mg_2Si)_P + (Mg_2Si + Al)_E$$

According to the Al-Ti and Al-Mg-Si phase diagrams [13,14], Ti will react with Al in the melt to generate intermetallic compounds $TiAl_3$ with a relatively high melting point when the Ti content is higher than 0.15wt.%. Since there is no coherent or semi-coherent lattic plane between $TiAl_3$ and Mg_2Si due to their different crystal structures, $TiAl_3$, therefore, can not act as the heterogeneity nuclei of Mg_2Si phase under normal circumstances. However, $TiAl_3$ particles can serve as heterogeneous nuclei of α-Al phase during solidification of Al-Mg_2Si alloy due to the existence of matched lattice planes. Meantime, the growth refined factor (GRF) of Ti element becomes stronger and the solute elements are more difficult to diffuse, and thus the growth rate of α-Al phase is suppressed. In addition, the refinement of the α-Al matrix and the great number of dispersed $TiAl_3$ phases precipitated in the matrix, as shown in Fig. 4 and Fig. 7, will significantly limit the relative growth space of Mg_2Si and hinder its growth, which will eventually lead to the refinement of Mg_2Si phase.

Song et al. [15] found that the addition of element Ti (4wt.%) can give rise to precipitation of Al_3Ti phase in Al/15Mg_2Si/5Si melt before the precipitation of primary Mg_2Si particles, which prevents the formation of larger Mg_2Si particle clusters and results in in-situ Al/Mg_2Si FGMs with a smooth gradient distribution of primary Mg_2Si particles. Since the density of $TiAl_3$ is greater than that of the alloy liquid, which means that a too long holding time before solidification will cause $TiAl_3$ to sink and segregate, and results that the refinement effect of Al-18wt.%Mg_2Si microstructure is reduced, which is consistent with the experimental results in this study.



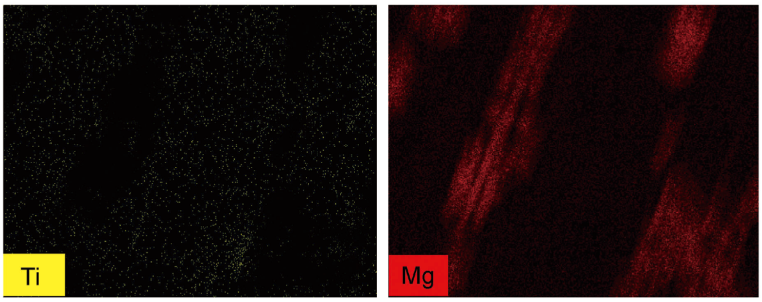


Fig. 7: Typical microstructure and element distribution of Al-18wt.%Mg_2Si-0.9wt.%Ti alloy

4 Conclusions

In this work, the effect of different addition of Ti and holding time on the microstructure and mechanical properties of electromagnetic stirred Al-18wt.%Mg_2Si alloy was studied and the following conclusions can be drawn.

(1) There are only α-Al phase, Mg_2Si primary phase and Al+Mg_2Si eutectic microstructure in the electromagnetic stirred Al-18wt.%Mg_2Si-*x*wt.%Ti alloys. The primary Mg_2Si phase in the alloy has the best refining effect and the most uniform distribution when the Ti content and holding time are 0.5wt.% and 20 min, respectively, and the mechanical properties of the alloy reach the highest value as well.

(2) Ti can refine the primary Mg_2Si phase in the alloy benefit from the refinement effect of the $TiAl_3$ intermetallic on α-Al matrix. The refined matrix structure can effectively limit the relative growth space of Mg_2Si and hinder its growth.

(3) With the increase of Ti content, the ultimate tensile strength, elongation and hardness of Al-18wt.%Mg_2Si-*x*wt.%Ti alloy increase first and then decrease. The variation trend of mechanical properties follows the variation trend of the microstructure.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] Qin Q D. Study on microstructures and properties of Mg_2Si/Al composites. Changchun: Jilin University, 2008. (In Chinese)

[2] Gao Y J, Li Y W. Analysis of valence electronic structures of Al-Mg-Si alloy. Journal of Changde Teachers University, 2003, 15(4): 9–11. (In Chinese)

[3] Mohanty P S, Gruzleski J E. Mechanism of grain refinement in aluminum. Acta Metallurgica et Materialia, 1995, 43(5): 2001–2012.

[4] Liu Z X, Song T F, Xie J P, et al. Production and grain refinement of direct electrolytic low-titanium aluminium alloys. The Chinese Journal of Nonferrous Metals, 2003, 13(5): 1257–1261. (In Chinese)

[5] Li P J, Ye Y C, He L J. Valence electron structure analysis of refining mechanism of Sc and Ti additions on aluminum. Chinese Science Bulletin, 2009, 54(5): 836–841.

[6] Wang J H, Yi D Q. Effect of titanium on microstructure and properties of 2618 aluminum alloy. Hot Working Technology, 2002 (6): 1–2, 47. (In Chinese)

[7] Zhao S X, Li S P, Zhao D Q, et al. Effect of Li and Ti additions on L<=>α(A1)+Mg_2Si pseudobinary eutectic reaction. Journal of Materials Science & Technology, 1997, 13(6): 487–490.

[8] Zhao S X, Li S P, Zhao D Q, et al. The effect of Li and Ti on the phase constitution of α(A1)-Si pseudobinary eutectic composite. International Journal of Cast Metals Research, 1997, 10(1): 45–48.

[9] Wu X F, Zhang G A, Wu F F. Microstructural characteristics of Mg_2Si/Al composite under different superheat and electromagnetic stirring. Rare Metal Materials and Engineering, 2015, 44(3): 576–580. (In Chinese)

[10] Li Y M, Yu Y, Ren Y Y. Effect of electromagnetic stirring on microstructures and properties of Al-18Mg_2Si alloy. Journal of Shenyang University of Technology, 2009, 31(3): 281–285. (In Chinese)

[11] Zhang J, Fan Z, Wang Y Q, et al. Equilibrium pseudobinary Al-Mg_2Si phase diagram. Materials Science and Technology, 2001, 17(5): 494–496.

[12] Li Y M, Liu T Y, Chen S Y, et al. Effect of Ce inoculation on microstructure and mechanical properties of in situ Al-20%Mg_2Si composite. International Journal of Metalcasting, 2019, 13(2): 331–336.

[13] Yu J Q, Yi W Z, Chen B D, et al. Binary alloy state atlas. Shanghai: Shanghai Science and Technology Press, 1987. (In Chinese)

[14] Watanabe Y, Nakamura T. Microstructures and wear resistances of hybrid Al-(Al_3Ti+Al_3Ni) FGMs fabricated by a centrifugal method. Intermetallics, 2001, 9(1): 33–43.

[15] Song C J, Xu Z M, Li J G. Fabrication of in situ Al/Mg_2Si functionally graded materials by electromagnetic separation method. Materials and Desigh, 2007, 28(2): 427–433.