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ARTICLE

Effect of Sr Modification on Microstructures and Mechanical Properties of Al_3Ti/ADC_{12} Composites

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Abstract: The effects of Sr modification on the microstructure and properties of Al_3Ti/ADC12 composite were investigated. The microstructures and fracture surfaces of the composite were examined by optical microscope and SEM. Results show that the addition of Sr reduces the sizes of the *α*-Al primary phase and Al_3Ti particles and modifies the morphology of the composite. The optimum level of Sr content is 0.25 wt%, and the eutectic silicon changes from an acicular or short rod shape into a granule one. Coarse dendritic of the primary *α*-A1 phases is fully refined. Results also show that Sr addition leads to the improvement in mechanical properties. Compared with matrix alloys, the tensile strength and elongation of the composite are increased by 36.9% and 58%, respectively when the Sr addition is 0.25 wt%. Furthermore, fractographic examinations reveals that cleavage surfaces and brittle plain area could hardly be seen from the Al_3Ti/ADC12 composite with addition of 0.25 wt% Sr. The dimples are increased in quantity and diminished in size, deeper and well-distributed. The fracture appearances match the tendency of the tensile properties.

Key words: Sr modification; Al_3Ti/ADC12 composites; microstructures; mechanical properties; fracture

In recent years, PRAMC prepared by in situ reaction has been developed rapidly and has attracted great attention due to its high specific strength, surface without pollution, interface bonding firm simple process and stable performance[1-5]. Al_3Ti is used as a particle reinforced phase due to its high melting point, low density, high modulus, and good wettability with aluminum alloy, so the research of in situ Al_3Ti/Al composites have received extensive attention [6-14].

From the current study, the mechanical properties of the Al_3Ti/Al-Si composites depend not only on *α*-Al dendrites structures, but also on the sizes and morphologies of eutectic Si and Al_3Ti particles. Chen et al. [10] fabricated Al_3Ti/Al composites by adding K_2TiF_6 powders into Al liquid at 1100 °C. The results revealed that Al_3Ti particles were presented in needle-shape with the length of 200μm and the width of 10 μm in the synthesized composites. Jie et al. [11] fabricated Al_3Ti/ADC12 composites by adding Ti-Al powders into Al liquid. The report revealed that the morphology of Al_3Ti phase was presented in bone-shape with the average length >100 μm. From these reports, due to the rapid atomic diffusion speed in high temperature melt and easily coarsening Al_3Ti, the size tends to reach tens of microns or even hundreds of microns, which greatly restricts the melt in situ reaction method application for Al_3Ti particles reinforced composites. For the purpose of improving the mechanical properties of Al-Si composites, some special elements have been added into the melt to modify the morphologies of the matrix and particles. Chen et al. [14] found that Y atoms could restrain the precipitation during solidification and then result in the morphology tending to be consistent of short rob with the size of 10 μm. Ludwig et al. [15] investigated the effect of Ca and P interaction on the Al-Si eutectic.

However, few works about the effects of Sr modification agent on the microstructures and mechanical properties of

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in situ synthesized Al_3Ti/ADC12 composites have been reported. In this paper, the Sr-modified Al_3Ti/ADC12 composites with different Sr contents were fabricated by melt in-situ reaction. This work mainly investigated the influence of Sr on the microstructures and mechanical properties of Al_3Ti/ADC12 composites. The mechanisms governed by Sr were also proposed from the obtained results.

1 Experiment

Commercial ADC12 aluminum alloy was chosen as matrix in this study, and the chemical composition is shown in Table 1. Firstly, to remove water, the Na_3AlF_6 and titanium (Ti) reactant powders were dehydrated at 150 °C for 3 h, where the mass ratio of Na_3AlF_6 and Ti was 1:1. At the same time, the alloy was melted in a graphite crucible at 820 °C by an electrical resistance furnace. After the alloy was completely melted, the ADC12-3 wt% Ti mixed powder was added into the melt. The melt was isothermally held at 820 °C for about 10 min to ensure the reaction completely, and then obtained Al_3Ti/ADC12 composites was attained. After this in situ reaction, the composite melt was cooled to about 760 °C. The Al-10% Sr master alloys were injected into the melt at 740 °C to result in the different additions of 0.1 wt%, 0.25 wt%, 0.4 wt% Sr to melt, respectively. And then the melt was held at 820 °C for about 10 min to ensure the reaction completely. The metal was finally poured into a metal mould, which was preheated for 200 °C. For the purpose of comparison, the Al_3Ti/ADC12 composite without Sr was also prepared by the same fabrication process.

The specimens were sampled at the same position of the ingot casting with the corresponding grinding, polishing, cleaning, and drying. The metallographic samples were etched using 0.6% hydrofluoric acid solution after polishing. Microstructures were observed using the Nican M300 metallographic microscope. Composites were processed into standard tensile test bars according to the standard GB/T 228-228, and the tensile tests were carried out by the CSS-44200 testing machine at a crosshead speed of 0.5 mm/min. The fractured surfaces of tensile samples were observed and analyzed using the NOVA NANOSEM 450 scanning electron microscope (SEM) equipped with INCA 250X-MAX 50 energy dispersive spectroscopy (EDS). Phase analyses were performed using an X-ray diffraction (XRD).

2 Experimental Results

2.1 Microstructural characterization

Fig.1 shows XRD patterns of the composites. It can be seen that, in addition to Al, $CuAl_2$ and Si diffraction peaks, there exists a peak of Al_3Ti. Fig.2a shows the typical microstructure of the Al_3Ti/ADC12 fabricated without Sr.

Table 1 Chemical composition of ADC12 alloy (wt%)

Si	Cu	Mg	Zn	Fe	Mn	Al
9.6	2.2	0.25	0.06	0.8	0.4	Bal.

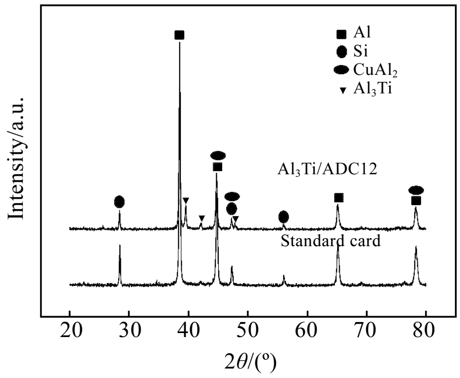


Fig.1 XRD patterns of Al_3Ti/ADC12 composites

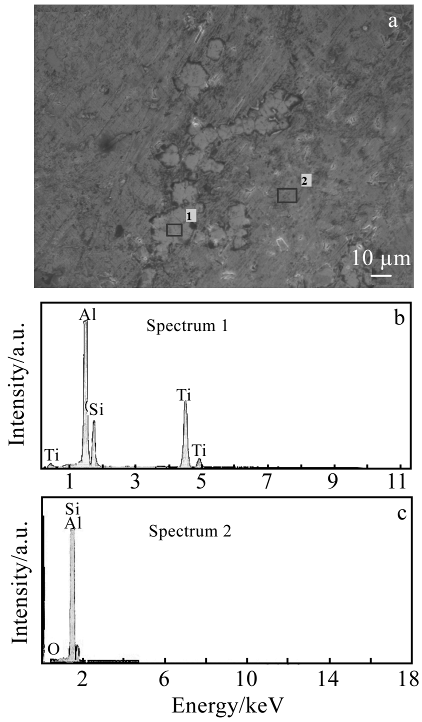
Lots of platelet and polygon-like phases can be observed. The EDS analysis shows that the main elements of the particles are Al, Si, and Ti, as shown in Fig.2b. Combined with the atomic percentages of Al and Ti, it can be proved that the Al_3Ti/ADC12 composites were successfully fabricated via in-situ reaction synthesis.

Fig.3 shows the optical microstructures of Al_3Ti/ADC12 composites prepared with different addition of Sr. α-Al coarse dendrite is observed in Fig.3a with a size of about 65 μm. It can also be seen from Fig.3a that the eutectic silicon particles exhibit a long needle or short rod structure. The eutectic silicon particles are distributed between the α-Al dendrites. Meanwhile, the plate-like Al_3Ti phase has obvious agglomeration.

In contrast, the microstructures are significantly modified when the Al_3Ti/ADC12 composites are added by Sr. The α-Al primary phases display a finer structure with the average size <50 μm when Sr addition is 0.1 wt%. The eutectic silicon particles exhibit a granular and globular structure. Nevertheless, some plate-like Al_3Ti particles can also be seen in microstructure.

In accordance with Fig.3c, the α-Al primary phase exhibits an ellipsoid and globular grain microstructure with the size of about 15 μm when Sr addition is 0.25 wt%. The eutectic silicon particles are obviously spheroidized. Meanwhile, the structure of Al_3Ti particles are changed from plate to globular and homogeneously distributed with the size of about 5 μm.

As shown in Fig.3d, when 0.4wt% Sr is added into the alloy, the refined α-Al phase grows up by the way of swallowing each other, which results in the generation of rose-shape α-Al phase with the diameter of 40 μm. At the same time, the eutectic Si phase occurs and grows up, and the agglomeration of plate-like Al_3Ti phase reappears.



EDS results of micro-zone 1 in Fig.2a

Element	wt%	at%
Al K	52.16	62.24
Si K	11.83	13.56
Ti K	36.01	24.20
Total	100.00	

Fig.2 SEM image (a) and EDS analysis (b, c) of the composite

2.2 Mechanical properties

Fig.4 shows the mechanical properties of Al_3Ti/ADC12 composites with different Sr additions. Accordance to Fig.4, the tensile strength and elongation of alloy have increased when Sr content is increased from 0 to 0.25 wt%. The Al_3Ti/ADC12 without Sr shows a relatively low tensile strength (205.81 MPa) and elongation (1.62%). When 0.1 wt% Sr is added, the tensile strength and the elongation of the composite are improved to 257.34 MPa and 2.4%, respectively. When 0.25 wt% Sr is added, the tensile strength and the elongation ratio of the composite are improved to 281.74 MPa and 2.6%, respectively. Compared with the Al_3Ti/ADC12 composites without Sr addition, the tensile strength and the elongation of this composite are increased by 36.9% and 58%. However, the tensile strength and elongation of the composite decrease to 264.59 MPa and 2.4%, respectively when the Sr content is increased to 0.40 wt%.

Excellent mechanical properties are largely dependent on the microstructural characteristics. Under the applied stress, the reinforcements act as an obstacle of slip owing to the dislocation and vacancies formed by the particles, and then improve the tensile strength. However, the coarse particles or worse bonding with the matrix are easily to produce stress concentration and brittle fracture.

Comparing with the Al_3Ti/ADC12 composite without Sr addition, the tensile strength and elongation ratio of Sr modified composites are superior. The particles are refined and its distribution becomes uniform. Nevertheless, when the Sr content reaches to 0.4 wt%, the mechanical

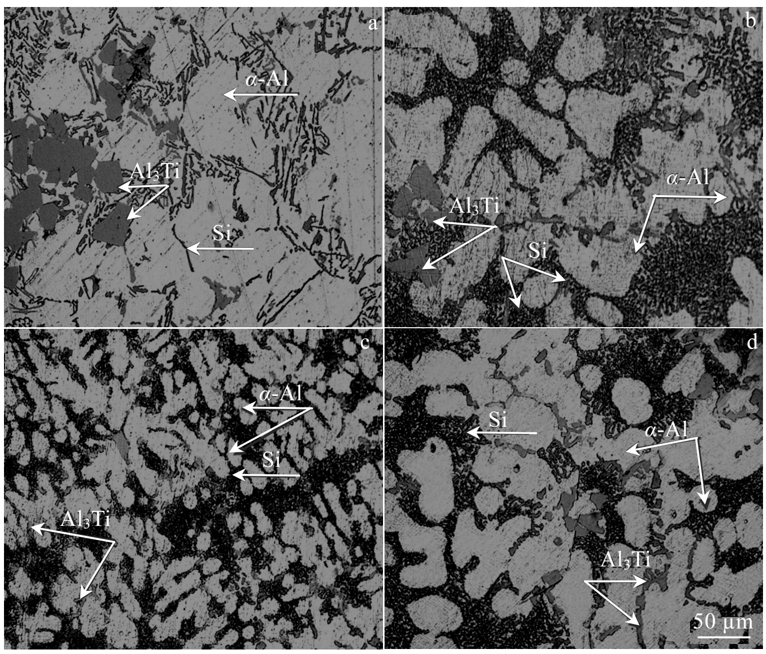


Fig.3 Microstructures of the Al_3Ti/ADC12 composites with different Sr addition: (a) 0 wt%, (b) 0.1 wt%, (c) 0.25 wt%, and (d) 0.4 wt%

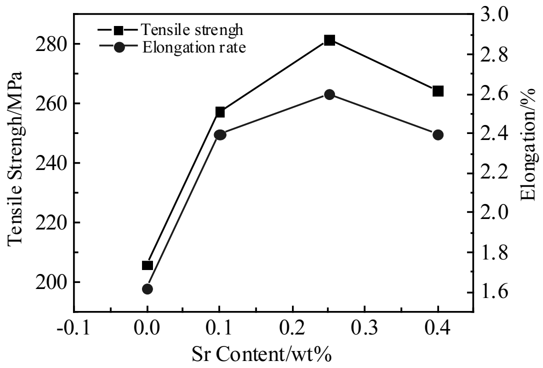


Fig.4 Mechanical propertirs of Al_3Ti/ADC12 composites

properties of the material slightly decrease due to stress concentration, grain coarsening and agglomeration of Al_3Ti particles.

2.3 Fracture characteristics

Fig. 5 exhibits the SEM fractographs of Al3Ti/ADC12 composites with different additions of Sr. As shown in Fig. 5a, some flush and shining herringbone patterns exist in the fracture surface of the unmodified material, but almost no dimples could be found. As shown in Fig. 5b, the fracture surface exhibits less brittle plain area, the big brittle plain area almost disappears, and the shorter tearing ridges distribute in the alloy, but the characteristics of dimples is not obvious, which mainly indicates favorable ductile behavior. As shown in Fig.5c, it can be found that cleavage surfaces and brittle plain area can hardly be seen from the Al_3Ti/ADC12 composite added with 0.25 wt% Sr, torn edges become tiny and evenly, the dimples are increased in quantity and diminished in size, deeper and well-distributed, and the characteristic of ductile fracture is obvious. In accordance with Fig.5d, the brittle plain area reappears, and the fracture surfaces gradually grow up and unevenly distribute in the alloy, indicating the favorable brittle behavior. The results of fracture appearance match the tendency of the tensile properties.

3 Discussion

In summary, the Sr addition has significantly influences on the microstructures of the α-Al coarse dendrite, the eutectic silicon and the Al_3Ti particles. The refinement mechanism of the α-A1 dendrite will be discussed in the next section.

According to Qiu et al.[16], the secondary dendrite arm spacing can be expressed as:

$$\lambda = 5.5 \times \sqrt[3]{(Mt_f)} \quad (1)$$

$$M = \frac{\Gamma D \ln(\frac{C_1}{C_0})}{m(1-K)(C_0 - C_1)} \quad (2)$$

$$K = C_S / C_L \quad (3)$$

Where λ is the secondary dendrite arm spacing; t_f is local solidification time; Γ is Gibbs Thomson coefficient; D is diffusion coefficient; C_0 and C_1 refer to the concentration of original alloy and eutectics; K is distribution coefficient; C_S and C_L refer to the equilibrium solid solubility and the equilibrium liquid solubility, respectively.

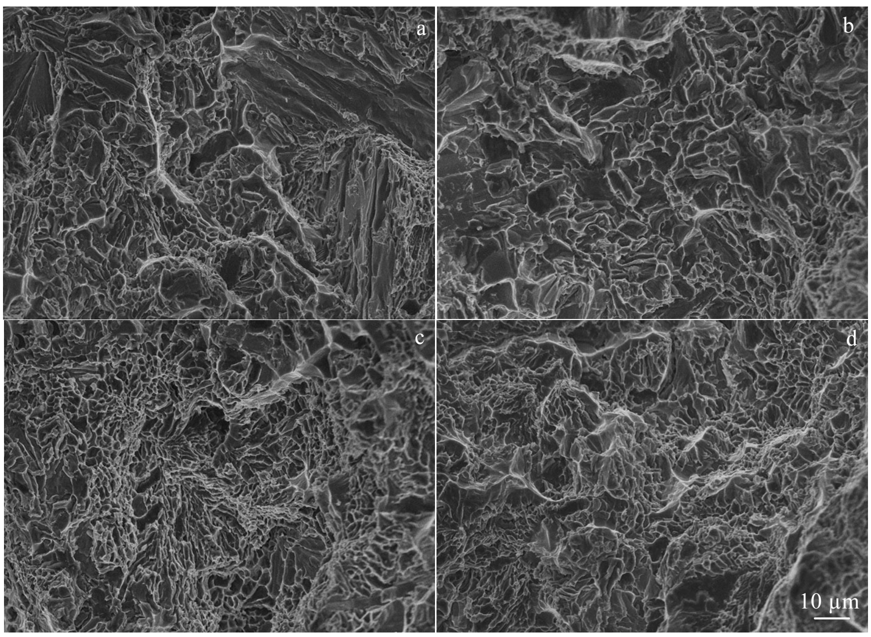


Fig. 5 Fractographs of the tensile samples with different Sr addition: (a) 0 wt%, (b) 0.1 wt%, (c) 0.25 wt%, (d) 0.4 wt%

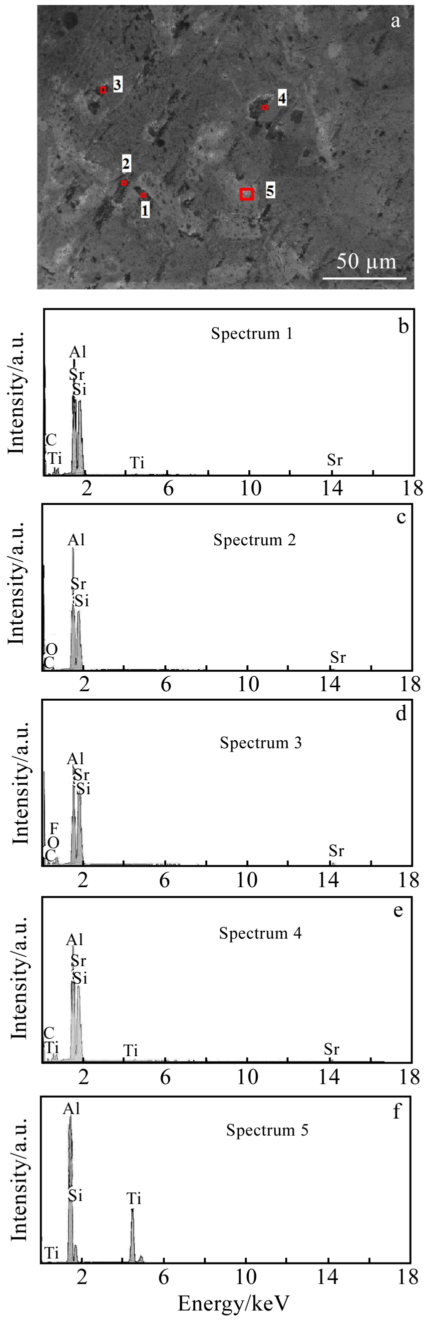


Fig.6 SEM micrograph (a) and EDS spectra (b~f) marked locations in Fig.6a for Al_3Ti/ADC12 with 0.25 wt% Sr

It can be seen from the Eq.(1), the secondary dendrite arm spacing (λ) depends on value of the M and local solidification time (t_f). According to Hume-Rothery rules[16, 17], when the atomic radius difference of solute and solvent is greater than 15%, only low solid solubility could form in the alloy composite. Nevertheless, the difference of atomic radii between Sr (0.245 nm) and Al (0.143 nm) is about 71.33%; therefore the chance for Sr entering primary phase of alpha-lambda lattice is pretty low. In other words, the solubility of Sr in composite is low. Generally, Sr is easy to aggregate at the solid-liquid interface, and thus inhibits the diffusing of solute atoms. Then the phase equilibrium solubility of C_L increases. decreasing the value of distribution coefficient K and M Consequently, we could conclude that doping with Sr has effects on the decrease of the secondary dendrite arm spacing.

The addition of Sr also has dramatic effects on the microstructure of the eutectic silicon. Sr modification agent can change the shape of the eutectic silicon from acicular or short rod into granule according to Fig. 3. The phenomenon can be explained by the impurity induced twinning mechanism[18,19]. Additionally, due to the Sr addition, chemical potential is improved. And it results in the improvement of the nucleation and growth of the α-Al primary phases, which greatly hinders growth of the eutectic silicon in turn, and leads to the changing shape of the eutectic silicon from needle to granule eventually.

As to the mechanism of Sr refining Al_3Ti, it is due to Sr barely dissolves to Al, instead Sr accumulates around solid-liquid interface. Fig. 6 show SEM morphology and EDS analysis of Al_3Ti/ADC12 with 0.25wt% Sr. As shown in Fig.6, Sr doesn't dissolve into Al matrix, but exists around Al_3Ti, hereinafter resulting in supercooling which leads to refinement of the Al_3Ti phase. Moreover, the addition of Sr decreases the eutectic temperature, and reinforces crystallization undercooling degree and thus results in refinement of Al_3Ti phase. Additionally, the existence of Sr improves chemical potential of α-Al and reinforces the capacity of nucleation and growth during eutectic solidification. As α-Al is easy to nucleate, it restrains the accumulation of Al_3Ti. Capacity of the nucleation has been improved due to the addition of Sr, as our previous discussed; hence the growth of Al_3Ti phase becomes more difficult.

4 Conclusions

1) Na_3AlF_6 and titanium powder (1:1) are successfully used for fabrication of Al_3Ti/ADC12 composites by the technology with melt in-situ reaction.

2) The addition of Sr greatly causes the grain refinement phase and eutectic silicon particles. When the addition of Sr was 0.25 wt%, the α-Al primary phase exhibits an ellipsoid and globular grain microstructure with the size of about 15 μm. The eutectic silicon particles are obviously spheroidized and homogeneously distributed. Meanwhile, microstructures of Al_3Ti particles are changed from plate to globular and well- distributed with the size of about 5 μm.

3) The addition of Sr significantly improves the tensile properties of materials. Compared with the Al_3Ti/ADC12 composites without Sr, the tensile strength and elongation ratio of 0.25 wt% Sr modified composites are increased by 36.89% and 58.02%, respectively.

4) The Al_3Ti/ADC12 composite unmodified exhibits brittle fracture behavior. However, due to the modification of Sr, the number of dimples increases in the fracture surface of the Al_3Ti/ADC12 composites, and the fracture surfaces of the sample show a clear ductile fracture nature.

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Sr 对合成 Al_3Ti/ADC12 复合材料微观组织与力学性能的影响

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摘 要：研究了不同含量的改性剂Sr对原位合成Al_3Ti/ADC12复合材料微观组织及力学性能的影响。通过光学显微镜以及扫描电镜观察复合材料的微观以及断口组织。结果表明：Sr的加入能有效减小α-Al以及Al_3Ti颗粒尺寸以及优化材料组织形态。Sr的最优加入量为0.25%（质量分数）。在该加入量条件下，共晶硅由针状或短棒状变为颗粒状，α-A1粗枝晶得到较好的细化，抗拉强度以及延伸率相对基体材料增加了36.9%和58%。断口形貌表明，在最优加入量条件下所制备的复合材料断口几乎看不到解理面和脆性平坦区，韧窝数量增多，韧窝尺寸变得更小且深，同时分布也较为均匀。断口形貌的特征与材料力学性能变化相一致。

关键词：Sr 变质；Al_3Ti/ADC12 复合材料；显微组织；力学性能；断口

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