

Effect of Al-8Sr-8Ce master-alloy content on microstructure and mechanical properties of Al-15Mg₂Si alloy

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Abstract: Al-Mg₂Si alloys exhibit broad application prospects in automotive, aerospace, and electronics fields. However, the coarse morphology of Mg₂Si constrains their applications. In this study, an Al-8Sr-8Ce modifier was proposed to improve the Mg₂Si morphology and mechanical properties of Al-15Mg₂Si alloys. The experimental results show that the addition of Al-8Sr-8Ce modifier transforms coarse, irregular flaky primary Mg₂Si phases into fine polygonal grains and refines the coarse Chinese-script-like eutectic Mg₂Si phases into fine fibrous structures. As the addition of Al-8Sr-8Ce increases from 0 to 0.4wt.%, both primary and eutectic Mg₂Si phases are gradually refined with enhanced distribution uniformity. When the Al-8Sr-8Ce content further increases to 0.5wt.%, the average size of primary Mg₂Si phase increases nearly by 100% compared to that with 0.4wt.% modifier, and the eutectic Mg₂Si transforms into a thin-sheet interconnected dendritic structure. Therefore, the optimal content of Al-8Sr-8Ce is 0.4wt.%. Under this condition, the average diameter of the primary Mg₂Si phase decreases to 11.95 μm, and the ultimate tensile strength and elongation attain 184 MPa and 4.0% respectively, which are 7.6% and 60.0% higher than those of the unmodified alloy. Excessive addition of the Al-8Sr-8Ce induces massive precipitation of Al₂Si₂Sr with a high formation temperature, which consume Sr and Ce elements and weaken the poison adsorption effect. This results in a decrease in both the strength and ductility of the alloy.

Keywords: Al-15Mg₂Si alloy; Al-8Sr-8Ce modification; primary Mg₂Si phase; eutectic Mg₂Si; mechanical properties

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1 Introduction

The Al-Mg₂Si alloy has a great application potential in the aerospace and automotive industries^[1-2]. The in-situ formed Mg₂Si phases in Al-Mg₂Si alloys show a high elastic modulus of 120 GPa, a low density of 1.99 g·cm⁻³, and a low coefficient of thermal expansion of

$7.5 \times 10^{-6} \text{ K}^{-1[3]}$. Nevertheless, Mg₂Si phases formed under normal as-cast conditions exhibit coarse morphologies with sharp edges and corners. This can damage the matrix material and is unfavorable for enhancing the alloy's performance^[4], limiting the widespread application of Al-Mg₂Si alloys.

It has been reported that adding modifying elements can effectively improve the morphology and size of primary and eutectic Mg₂Si phases, and further enhance the comprehensive mechanical properties of the alloy. Over the past decades, multiple elements including Sr, rare earth (RE), Li, and Bi have been verified to possess favorable modifying effects^[4-9]. Qin et al.^[5] reported that trace Sr additions transformed dendritic primary Mg₂Si phases to polygon, decreasing its equivalent diameter by 80%.

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The underlying modifying mechanism is interpreted as the adsorption of Sr atoms on the solidification front of Mg_2Si phases, which restricts crystal growth. Wu et al.^[8] discovered that the morphology of primary Mg_2Si transformed from irregular or dendritic to polyhedral by adding moderate Bi, and the average equivalent diameter decreased from 70 μm to 6 μm . Meanwhile, eutectic Mg_2Si phase transformed into short fibrous and granular morphologies. Li et al.^[6] found that incorporating 0.6wt.% Ce into the Al-20Mg₂Si alloy reduced the average diameter of primary Mg_2Si phase to below 24 μm . Compared with the unmodified alloy, the tensile strength, elongation, and hardness of the Ce-modified alloy increased by 34.4%, 29.1%, and 22.1%, respectively. Hisham et al.^[10] investigated the influence of different Er contents (ranging from 0.0 to 1.0wt.%) on microstructure of hypoeutectic Al-11Mg₂Si alloy, and confirmed that 0.1wt.% Er changed the flaky eutectic Mg_2Si phase into fibrous structures. Previous studies^[11] have demonstrated that, compared with single Sr or Ce additions, the composite Al-8Sr-8Ce modifier presented a more pronounced effect on the morphology and size of both primary and eutectic Mg_2Si phases simultaneously, thereby significantly enhancing the mechanical properties of the alloy. This research presented a new approach for improving the plasticity of in-situ formed Al-Mg₂Si alloy. Nevertheless, the optimal addition level of Al-8Sr-8Ce for the Al-15Mg₂Si alloy has not yet been determined.

In this study, Al-15Mg₂Si alloys with different Al-8Sr-8Ce modifier contents were fabricated using gravity casting. The effects of modifier concentration on the microstructure evolution and mechanical properties of the Al-15Mg₂Si alloy were investigated, and the relevant evolution mechanism was discussed. The findings of this work offer the optimal Al-8Sr-8Ce content for the modification of Al-15Mg₂Si alloys.

2 Experimental materials and methods

The Al-15Mg₂Si alloys were fabricated using commercial pure Al (purity>99.7%), commercial pure Mg (purity>99.8%), Al-20Si and Al-8Sr-8Ce intermediate alloys. The Al-8Sr-8Ce alloy mainly consisted of $Al_4(Sr, Ce)$ and $Al_{11}(Ce, Sr)_3$ phases^[11]. The total mass of each melted alloy was fixed at 2,000 g, the preparation processes of these alloys are listed as follows:

First, placed pure aluminum and about 50% Al-20Si into a graphite crucible and heated to 800–820 °C in a high-temperature resistance furnace. Once all the raw materials were fully melted, the remaining Al-20Si master alloy was added to the melt. When the temperature decreased to 730–750 °C, approximately 10 g refining agent composed of chlorides and fluorides was introduced for melt purification. After holding for 10 min, the Al-8Sr-8Ce modifier and commercial pure magnesium were added. The melt was held at around 730 °C for 30 min and poured into a steel mold pre-heated to about 250 °C. In this work, six groups of alloys with varying Al-8Sr-8Ce addition contents (0.0wt.%, 0.1wt.%, 0.2wt.%, 0.3wt.%, 0.4wt.%, 0.5wt.%) were prepared.

All samples were cut at the same position, with a fixed distance from the ingot bottom. Subsequently, the actual chemical compositions of the alloys were measured using an optical emission spectrometer, and the corresponding results are listed in Table 1. The specimens were ground using #240 to #3000 grit silicon carbide sandpapers and polished with 5%–10% aqueous MgO solution. Optical microscopy (OM), scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and X-ray diffractometer (XRD) were employed to observe and analyze the microstructure and phase constitution of the alloys. To observe the three-dimensional (3D) morphology of Mg_2Si phases, deep etching was performed using a 15% NaOH solution. The Image-Pro Plus 6.0 software was employed to count the average size of Mg_2Si phases. Differential scanning calorimetry (DSC) was conducted to analyze the phase solidification sequence of the Al-Mg₂Si alloys, and the corresponding second-order derivative curves were drawn by Origin software. The mechanical properties of the alloys were tested on a universal mechanical testing machine at a constant tensile rate of 0.5 mm·min⁻¹.

3 Results

3.1 Microstructural characterization

Figure 1(a) shows that in the absence of a modifier, the primary Mg_2Si phases present coarse and irregular blocks with evident segregation. As displayed in Fig. 1(b), with the addition of 0.1wt.% Al-8Sr-8Ce, the primary Mg_2Si phase are significantly refined and transformed into polygonal

Table 1: Actual chemical compositions of experimental alloys (wt.%)

Al-8Sr-8Ce content	Si	Mg	Fe	Sr	Ce	Al
0	6.38	10.15	0.15	/	/	Bal.
0.1	6.32	10.22	0.17	0.005	0.005	Bal.
0.2	6.36	9.89	0.14	0.0097	0.010	Bal.
0.3	6.41	10.02	0.16	0.015	0.014	Bal.
0.4	6.28	10.09	0.13	0.019	0.020	Bal.
0.5	6.37	10.05	0.15	0.025	0.025	Bal.

morphologies, accompanied by markedly improved dispersion uniformity. As the content of the Al-8Sr-8Ce increases, the size of primary Mg_2Si phase further reduces. However, when the content of the Al-8Sr-8Ce reaches 0.5wt.%, the primary Mg_2Si phase coarsens suddenly, its morphology reverts from irregular polygons to coarse blocks and obvious phase segregation reappears.

Figure 2 depicts the high-magnification OM images of alloys with varying Al-8Sr-8Ce contents. In the unmodified alloy shown in Fig. 2(a), eutectic Mg_2Si phase presents as coarse, elongated strips, and Chinese-script-like morphologies. The addition of 0.1wt.% Al-8Sr-8Ce shortens the eutectic Mg_2Si structures and improves their dispersion uniformity, as shown in Fig. 2(b). As the content of Al-8Sr-8Ce increases, the coarse

long-strip eutectic Mg_2Si essentially vanishes and transforms into fibrous, fine script-like, and a small quantity of granular morphologies. When the Al-8Sr-8Ce content is 0.4wt.%, most eutectic Mg_2Si phases are transformed into fine granular structures, while sporadic script-like phases remain at the peripheries of the eutectic Mg_2Si phase. When the content of the Al-8Sr-8Ce further reaches 0.5wt.%, eutectic Mg_2Si phase becomes coarser and their morphologies convert to coarse elongated strips, resulting in severe phase segregation.

A total of 100 primary Mg_2Si phases were randomly chosen from Al-15 Mg_2Si alloys with varying Al-8Sr-8Ce contents for statistical analysis of equivalent diameter. Figure 3 shows the average equivalent diameter of the primary Mg_2Si phase in the unmodified Al-15 Mg_2Si alloy amounts to 17.65 μm .

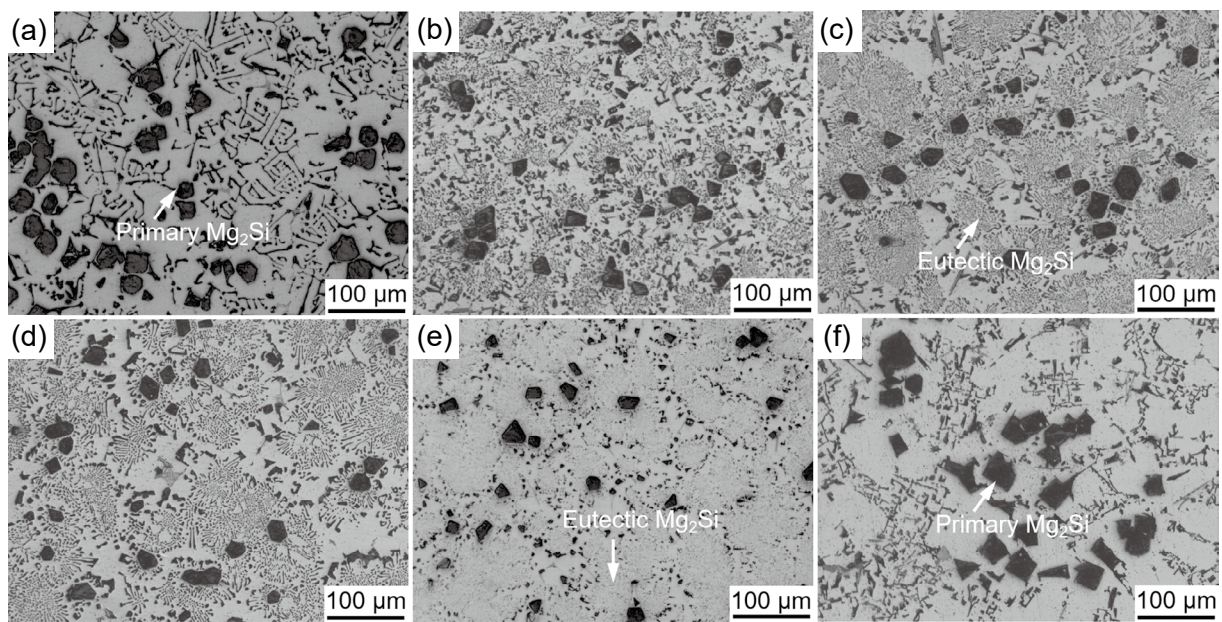


Fig. 1: Low-magnification OM images of Al-15 Mg_2Si alloys with different Al-8Sr-8Ce contents: (a) 0wt.%; (b) 0.1wt.%; (c) 0.2wt.%; (d) 0.3wt.%; (e) 0.4wt.%; (f) 0.5wt.%

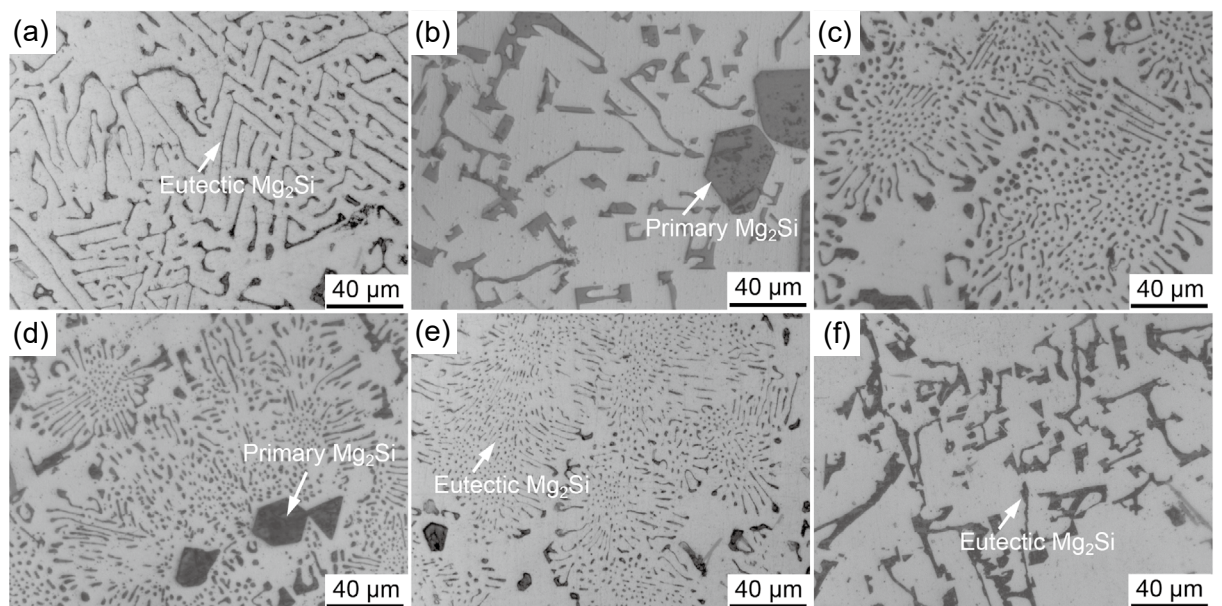


Fig. 2: High-magnification OM images of Al-15 Mg_2Si alloys with different Al-8Sr-8Ce contents: (a) 0wt.%; (b) 0.1wt.%; (c) 0.2wt.%; (d) 0.3wt.%; (e) 0.4wt.%; (f) 0.5wt.%

After adding 0.1wt.% Al-8Sr-8Ce, this value drops to 14.15 μm , corresponding to a 19.8% reduction. With 0.2wt.% and 0.3wt.% Al-8Sr-8Ce additions, the average equivalent diameter decreases to 13.45 μm and 13.35 μm , representing refinements of 23.8% and 24.3%, respectively, compared with the unmodified alloy. The minimum average equivalent diameter of the primary Mg_2Si phase is about 11.6 μm with 0.4wt.% Al-8Sr-8Ce addition, with a total reduction of 32.3% compared

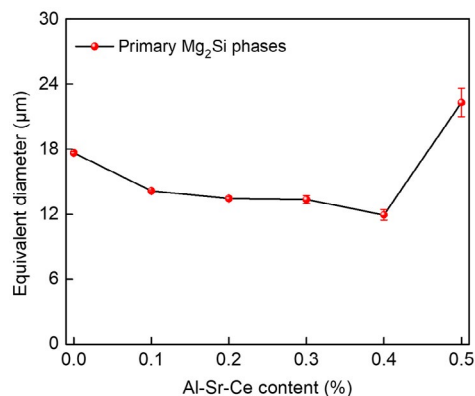


Fig. 3: Average equivalent diameter of primary Mg_2Si phases in Al-15 Mg_2Si alloys with different Al-8Sr-8Ce contents

to the base alloy. When the content of the modifier further reaches 0.5wt.%, the average equivalent diameter of the primary Mg_2Si phase increases to 22.30 μm , approximately twice the diameter measured at 0.4wt.% content.

Figure 4 depicts the deeply-etched images of the primary Mg_2Si phase in Al-15 Mg_2Si alloys with varying Al-8Sr-8Ce contents. When the content of the Al-8Sr-8Ce rises from 0.1wt.% to 0.4wt.%, the primary Mg_2Si phase consistently exhibits polyhedral morphologies. When the modifier content further rises to 0.5wt.%, primary Mg_2Si assumes regular cubic morphologies, which may be attributed to the increase in Sr content. Qin et al.^[5] pointed out that Sr addition drives primary Mg_2Si phase to grow from octahedral contours and ultimately develop cubic contours. At low modifier concentrations, the adsorption effect of the modifying elements primarily reduces the migration of Mg and Si atoms from grain tips to the planes, facilitating preferential growth of $\{001\}$ crystal planes^[12]. As modifier content further increases, the growth rate of $\{111\}$ planes gradually declines and is eventually restrained to zero, whereas only $\{001\}$ planes remain retained. Therefore, when the content of Al-8Sr-8Ce is 0.5wt.%, the primary Mg_2Si phase transforms into a fully cubic morphology surrounded by $\{001\}$ crystal planes.

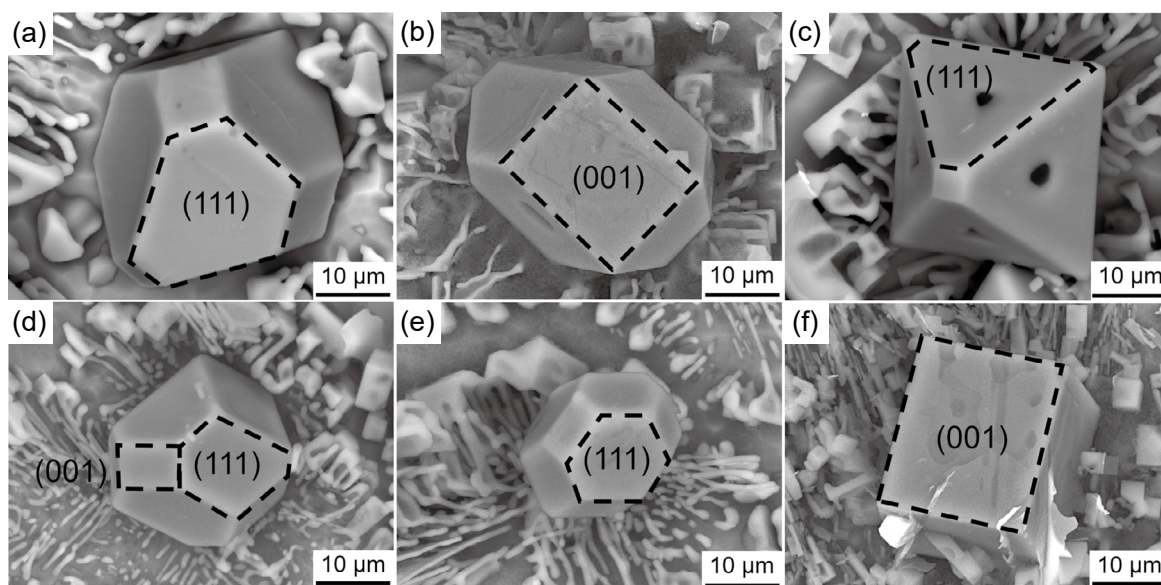


Fig. 4: Deep-etched images of primary Mg_2Si phase in Al-15 Mg_2Si alloys with different Al-8Sr-8Ce contents: (a) 0wt.%; (b) 0.1wt.%; (c) 0.2wt.%; (d) 0.3wt.%; (e) 0.4wt.%; (f) 0.5wt.%

Figure 5 presents the deep-etched morphologies of the eutectic Mg_2Si phase. As observed in Fig. 5(a), the eutectic Mg_2Si phase in the unmodified alloy displays a coarse multi-branched interconnected structure composed of uneven platelets. After adding Al-8Sr-8Ce, the eutectic Mg_2Si transforms into a fine fibrous gradually. As the content of the Al-8Sr-8Ce increases, some of granular Mg_2Si phases appear and exhibit relatively concentrated distribution, as shown in Figs. 5(c) and (d). The optimal refinement effect of the eutectic Mg_2Si phase is obtained at 0.4wt.% Al-8Sr-8Ce, and the eutectic phase transforms into uniformly distributed fine fibrous and granular structures, with only a few residual

flaky structures at eutectic phase boundaries, as shown in Fig. 5(e). At 0.5wt.% Al-8Sr-8Ce addition, the 3D morphology of eutectic Mg_2Si phase changes into complex dendritic structures, and massive bulk structures are found in the middle of the eutectic phases, as shown in Fig. 5(f).

XRD patterns of all experimental alloys are shown in Fig. 6, which reveal that all alloys consist of Al and Mg_2Si phases. No Sr-containing or Ce-containing intermetallic phases are identified by XRD, which may be attributed to their low volume fraction and fine dispersion, falling below the detection limit of the XRD. Therefore, further analysis is needed to prove whether these phases exist or not.

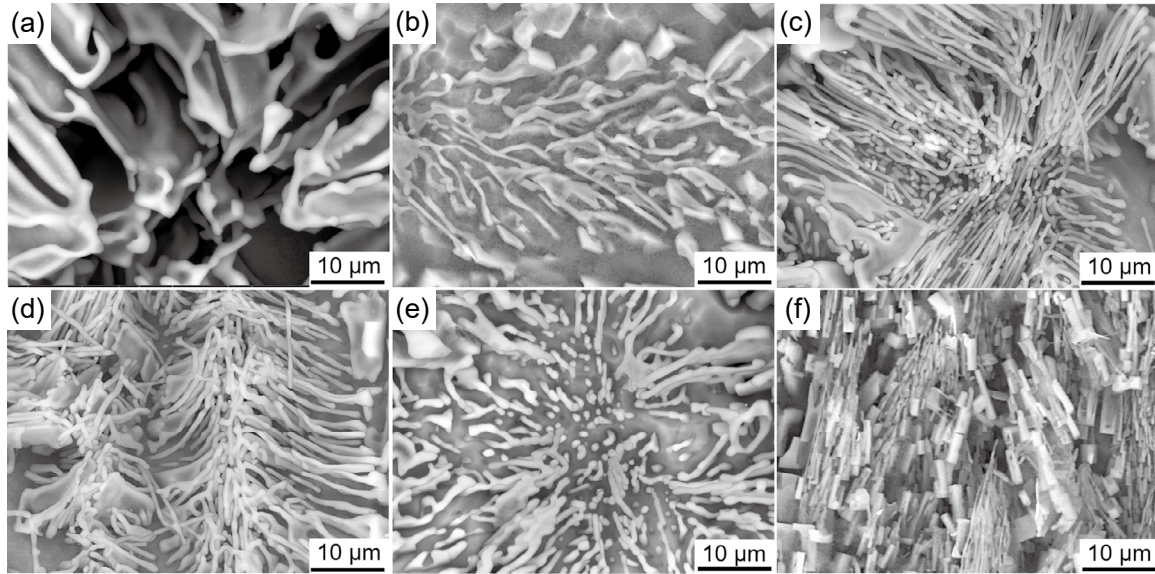


Fig. 5: Deep-etched morphologies of eutectic Mg_2Si phase in Al-15 Mg_2Si alloys with different Al-8Sr-8Ce contents: (a) 0wt.%; (b) 0.1wt.%; (c) 0.2wt.%; (d) 0.3wt.%; (e) 0.4wt.%; (f) 0.5wt.%

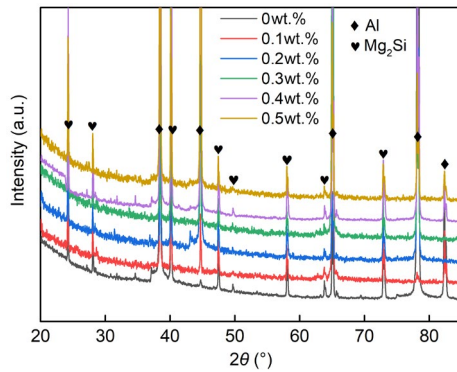


Fig. 6: XRD patterns of Al-15 Mg_2Si alloys modified with different Al-8Sr-8Ce contents

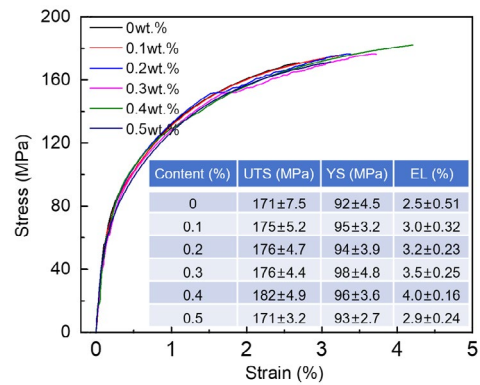


Fig. 7: Tensile curves of Al-15 Mg_2Si alloys with different Al-8Sr-8Ce additions

3.2 Mechanical properties

Figure 7 shows the tensile curves of Al-15 Mg_2Si alloys with different Al-8Sr-8Ce additions. As the content of the composite modifier increases, the ultimate tensile strength (UTS) has no obvious change, while elongation (EL) increases gradually until the addition of Al-8Sr-8Ce reaches 0.4wt.%. At 0.4wt.% Al-8Sr-8Ce, the alloy achieves optimal mechanical properties, its ultimate tensile strength and elongation reach 184 MPa and 4.0%, which are 7.6% and 60.0% higher than those of the unmodified alloy, respectively. When the content of the Al-8Sr-8Ce is 0.5wt.%, the ultimate tensile strength and elongation decline to 171 MPa and 2.9%, respectively. In the unmodified alloy, coarse blocky primary Mg_2Si and plate-like eutectic Mg_2Si can easily pierce the Al matrix under external forces, thereby degrading both strength and ductility of the alloy. The addition of Al-8Sr-8Ce modifier refines primary Mg_2Si phases and blunts their edges and corners, weakening the cutting effect of the primary Mg_2Si particles on the matrix. Moreover, eutectic Mg_2Si is transformed into fine fibrous and granular morphologies with a more homogeneous distribution, which diminishes stress concentration and slows crack propagation. Therefore, a higher elongation is achieved. When the content of Al-8Sr-8Ce rises to 0.5wt.%, abnormal coarsening occurs

in both primary Mg_2Si phase and the eutectic Mg_2Si phase, leading to a substantial decrease in the mechanical properties.

To further investigate the impact of the morphologies of Mg_2Si phases on mechanical properties of Al-15 Mg_2Si alloys, the fracture surfaces of Al-15 Mg_2Si alloy with varying Al-8Sr-8Ce contents were examined using SEM. The fracture surfaces are presented in Fig. 8, and cross-sectional fracture profiles are presented in Fig. 9. For the unmodified alloy shown in Fig. 8(a), the fracture surface is covered with numerous coarse and cleavage planes, where coarse Mg_2Si phases can be clearly discerned. The coarse and smooth cleavage planes are formed because microcracks initiate within the coarse Mg_2Si and propagate along phase interfaces. As the content of the modifier increases, the number, size, and area of cleavage planes gradually diminish, and numerous dimples emerge on fracture surface. As shown in Fig. 8(e), when the Al-8Sr-8Ce content reaches 0.4wt.%, dense tiny dimples dominate the fracture surface, exhibiting typical ductile fracture characteristics. Nevertheless, 0.5wt.% Al-8Sr-8Ce leads to reappearance of large smooth cleavage planes and a reduction in dimples density, as shown in Fig. 8(f), which promotes brittle fracture and reduces the tensile strength and elongation of the Al-15 Mg_2Si alloy.

As is evident from Fig. 9(a), cross-sectional fracture morphologies of the unmodified alloy reveal a large number of fractured primary Mg_2Si phases on the fracture path, suggesting that the fracture mode of this alloy is predominantly trans-granular fracture. Moreover, massive microcracks emerge at the interfaces between primary and eutectic Mg_2Si phases near the fracture, indicating coarse Mg_2Si phases act as major crack initiation sites. Cracks tend to initiate and expand along coarse flaky primary Mg_2Si phases and long-rod eutectic Mg_2Si phases, leading to premature brittle fracture after the initiation of tensile loading and resulting in low strength and poor elongation of the alloy. After Al-8Sr-8Ce modification, both primary and eutectic Mg_2Si phases are refined to a varying degrees. Particularly after the modification of 0.4wt.% Al-8Sr-8Ce, the average diameter of the primary Mg_2Si phase is decreased by 32.3% compared to that of the unmodified alloy, resulting markedly reduced cracks on primary Mg_2Si phase at fracture sections. At 0.5wt.% Al-8Sr-8Ce addition, primary and eutectic phases become notably coarser and substantial number of fractured primary Mg_2Si phases reappear

on fracture paths. These coarse Mg_2Si phases act as pathways for crack propagation, leading to a marked decrease in the mechanical properties of the alloys.

Refinement of eutectic Mg_2Si phase plays a critical role in enhancing the mechanical properties of the alloys. After adding Al-8Sr-8Ce, coarse long-strip and script-like eutectic Mg_2Si phases are notably refined with a greatly decreased aspect ratio. According to the fiber load theory^[13], the maximum stress ($\sigma_{\max}$) borne at the center of a grain follows an inverse proportional relationship with its aspect ratio and matrix shear stress (τ_m), as expressed in Eq. (1):

$$\left(\frac{l}{t}\right)_{\sigma_{\max}} = \left(\frac{l}{t}\right)_{\tau_m} \quad (1)$$

where l and t denote the maximum and minimum dimensions of the phase, respectively. This equation indicates that phases with greater aspect ratio are more prone to stress concentration, crack initiation, and premature fracture during tensile process. The eutectic Mg_2Si phase in unmodified alloy exists as coarse long-strips with large aspect ratios, which generate abundant

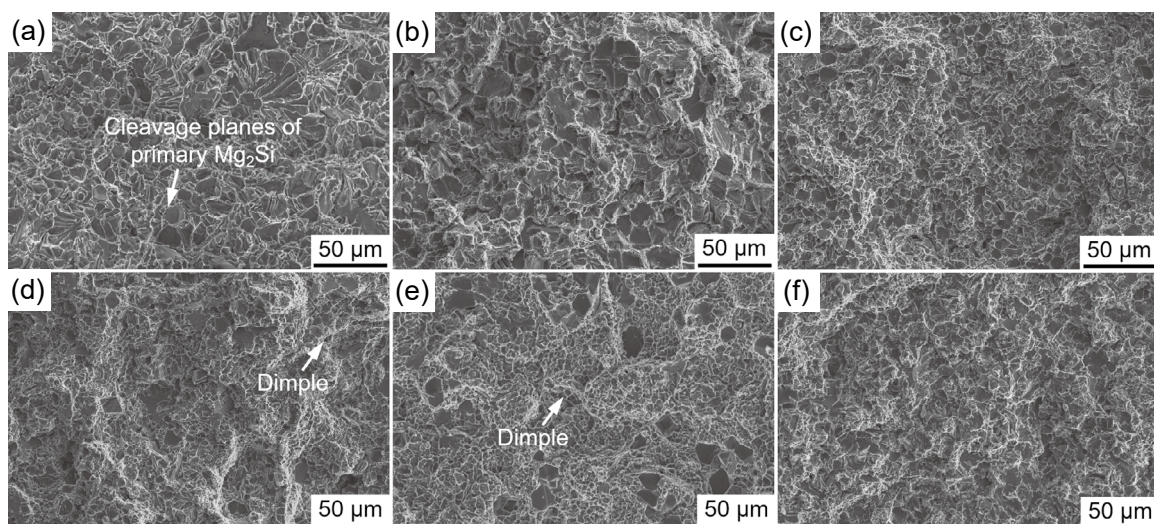


Fig. 8: Surface fracture morphologies of Al-15 Mg_2Si alloys with different Al-8Sr-8Ce contents: (a) 0wt.%; (b) 0.1wt.%; (c) 0.2wt.%; (d) 0.3wt.%; (e) 0.4wt.%; (f) 0.5wt.%

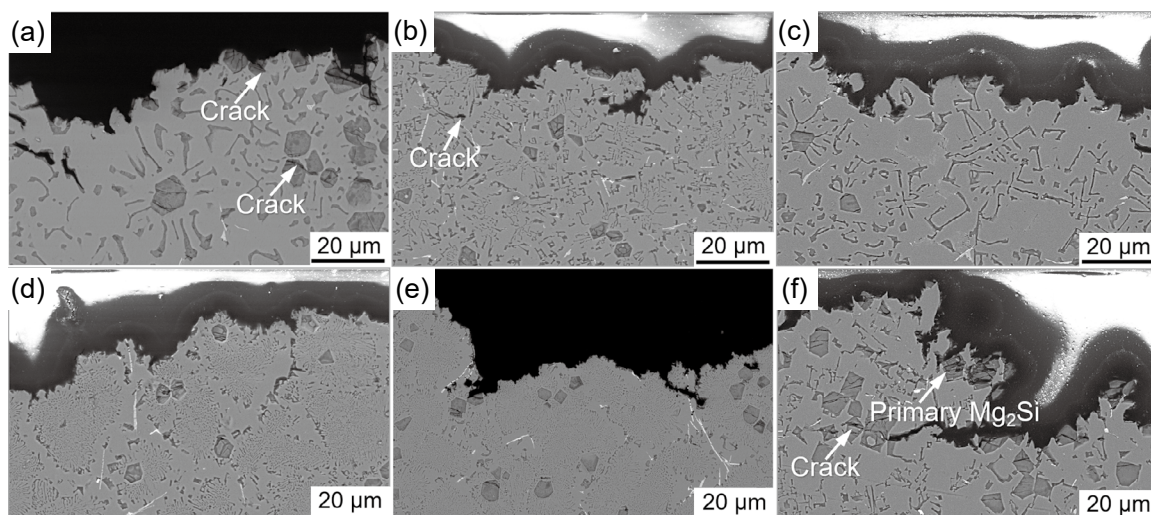


Fig. 9: Cross-sectional fracture morphologies of Al-15 Mg_2Si alloys with different Al-8Sr-8Ce contents: (a) 0wt.%; (b) 0.1wt.%; (c) 0.2wt.%; (d) 0.3wt.%; (e) 0.4wt.%; (f) 0.5wt.%

microcracks and degrade mechanical properties of the alloy. When the content of the Al-8Sr-8Ce modifier reaches 0.4wt.%, eutectic Mg_2Si phase is effectively refined and its aspect ratio decreases correspondingly. The initiation and propagation of microcracks are effectively suppressed, which simultaneously enhancing the strength and plasticity of Al-15Mg₂Si alloys.

4 Discussion

Figure 10(a) presents the DSC curves of Al-15Mg₂Si alloys, and Fig. 10(b) depicts the corresponding second-order derivative curves. In Fig. 10(a), three peaks A, B, and C respectively signify the solidification behavior of primary Mg_2Si , α -Al, and eutectic Mg_2Si phases. For the unmodified alloy, the initial and final solidification temperatures of primary Mg_2Si phase are 617.1 °C and 591.3 °C, respectively, providing a solidification temperature range of 25.8 °C. The initial and final solidification temperatures of eutectic Mg_2Si phase are 551.3 °C and 530.0 °C, respectively, with a temperature difference of 21.3 °C. The addition of Al-8Sr-8Ce significantly changes the initial and final solidification temperatures of both the primary and eutectic Mg_2Si phases. The minimum solidification temperature range for Mg_2Si phase is achieved at 0.4wt.% Al-8Sr-8Ce addition, and the temperature interval of primary Mg_2Si decreases from 25.8 °C for the unmodified alloy to 16.8 °C, while that of eutectic Mg_2Si decreases from 21.3 °C to 16.1 °C. However, further increasing the Al-8Sr-8Ce content induces a notable broadening of the Mg_2Si solidification temperature range. As illustrated in Fig. 10(b), the alloy modified with 0.5wt.% Al-8Sr-8Ce

exhibits a expanded primary Mg_2Si phase solidification temperature range of 31.8 °C, with the initial and final solidification temperatures measured at 621.3 °C and 589.5 °C, respectively. Likewise, the eutectic Mg_2Si phase exhibits a widened solidification temperature range of 20.1 °C, corresponding to an initial temperature of 546.1 °C and a final temperature of 526.0 °C.

The solidification sequence of Al-15Mg₂Si alloys was simulated by JmatPro thermodynamic software, and the calculated results are shown in Fig. 11. The simulation indicates that Mg_2Si phase precipitates preferentially during solidification of the unmodified alloy. As the content of Al-8Sr-8Ce increases, certain Sr- and Ce-containing compounds precipitate along with the solidification of the Mg_2Si phase. When the content of Al-8Sr-8Ce increases to 0.5wt.%, no new phases are formed in comparison with the 0.4wt.% modified alloy.

Back-scattered electron diffraction (BSD) images of Al-15Mg₂Si alloys with varying Al-8Sr-8Ce contents are presented in Fig. 12, and the chemical compositions of bright-white phases within the images analyzed via EDS are summarized in Table 2. In the unmodified Al-15Mg₂Si alloy, a small number of elongated bright-white β -Al₃FeSi compounds are found surrounding the eutectic Mg_2Si phases. After Al-8Sr-8Ce modification, granular bright-white phases emerge in the Al-15Mg₂Si alloys. The analysis results show that the granular bright-white phase contains Al, Mg, Si, Sr, and Ce, which are indicated as (Al, Mg)₂Si₂(Sr, Ce) phases. Some of these bright-white phases adsorb on the solidification front of the primary Mg_2Si phase, while others penetrate through the

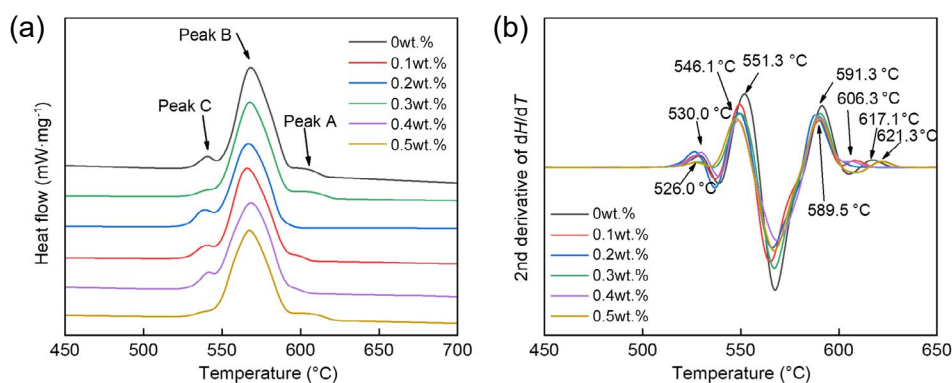


Fig. 10: DSC curves of Al-15Mg₂Si alloys with different Al-8Sr-8Ce contents: (a) DSC results; (b) 2nd derivative of dH/dT

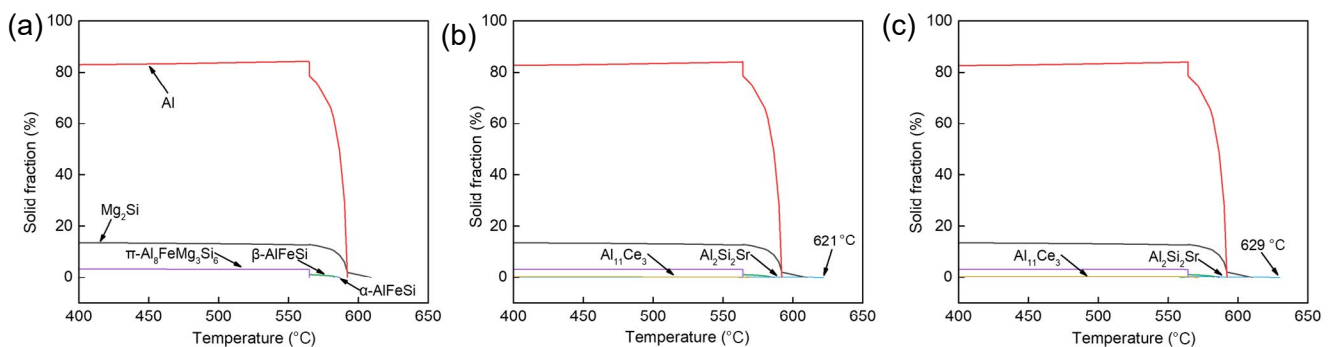


Fig. 11: Simulated solidification sequences of Al-15Mg₂Si alloys with different Al-8Sr-8Ce contents: (a) 0wt.%; (b) 0.4wt.%; (c) 0.5wt.%

eutectic Mg_2Si phase, effectively modifying both primary and eutectic Mg_2Si phases.

As the content of Al-8Sr-8Ce continues to increase, as depicted in Fig. 12(c), blocky bright-white phases emerge in the 0.5wt.% modified Al-15 Mg_2Si alloy. EDS results reveal that the composition of these blocky bright-white phases is consistent with that of Point C in Fig. 12(b), yet their numbers and area fraction increase significantly. Besides the formation of $(Al, Mg)_2Si_2(Sr, Ce)$, the Sr also reacts with elements like Al and Si to form a large number of Al_2Si_2Sr compounds, which is consistent with previous reports^[14-17]. As shown in Fig. 11, increasing the Al-8Sr-8Ce content from 0.4wt.% to 0.5wt.% raises the solidification temperature of Al_2Si_2Sr phase from 621 °C to 629 °C, which promotes the thermodynamic driving force for the formation of Al_2Si_2Sr . Therefore, increasing the Al-8Sr-8Ce content promotes the preferential solidification of Al_2Si_2Sr phase, consuming a large quantity of modification elements such as Sr and Ce. The amount of Sr in the melt that can be adsorbed on the Mg_2Si phase solidification front is reduced significantly, weakening the hindering effect on

Mg_2Si crystal growth and thus deteriorating the modification efficiency. Moreover, the preferentially precipitated Al_2Si_2Sr phase experiences excessive growth and severe coarsening, as depicted in Fig. 12(c).

Figure 13 shows a schematic diagram of the modification mechanism on Mg_2Si phase under different Al-8Sr-8Ce contents. With the optimal addition of Al-8Sr-8Ce, Sr and Ce atomic clusters form in the melt and inherit the microstructure of Al(Sr, Ce) phases in the composite modifier. Meanwhile, due to their low solid solubility and high activity, Sr and Ce atoms selectively adsorb on Mg_2Si grain surface, which hinders the growth of primary and eutectic Mg_2Si phases. In contrast, excessive Al-8Sr-8Ce leads to the preferential precipitation of massive Al_2Si_2Sr compounds prior to the formation of primary Mg_2Si , consuming a significant amount of Sr atoms. On the one hand, it decreases the diffusion efficiency of Si and Mg elements from the tips to the planes of Mg_2Si grains. On the other hand, it weakens the adsorption and poisoning effects on Mg_2Si phase, leading to an over-modification phenomenon and significantly diminishing the modification efficiency^[11, 14].

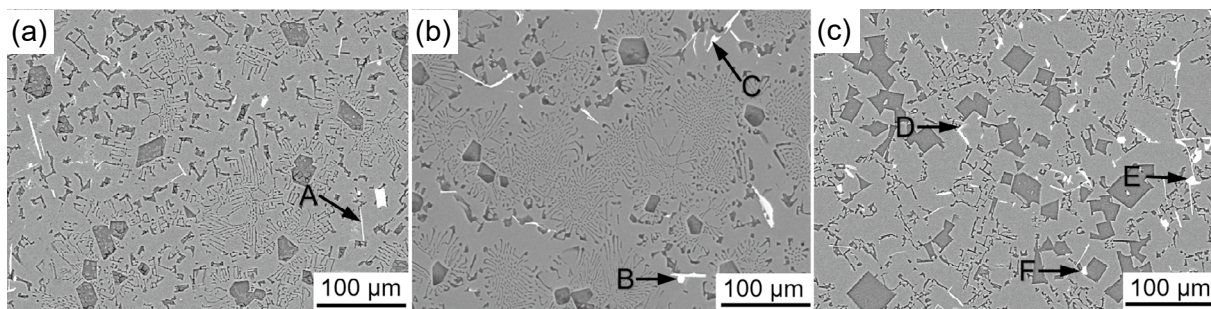


Fig. 12: BSD images of Al-15 Mg_2Si alloys with different Al-8Sr-8Ce contents: (a) 0wt.%, (b) 0.4wt.%, (c) 0.5wt.%

Table 2: Chemical composition of typical phases in Al-15 Mg_2Si alloys shown in Fig. 12 (wt.%)

Test point	Si	Mg	Fe	Sr	Ce	Al	Possible phase
A	10.7	/	16.1	/	/	Bal.	$\beta-Al_5FeSi$
B	24.9	/	4.5	/	11.9	Bal.	$\beta-Al_5(Fe, Ce)Si$
C	21.3	4.7	/	3.1	39.8	Bal.	$(Al, Mg)_2Si_2(Sr, Ce)$
D	11.5	/	21.1	23.9	17.3	Bal.	$\beta-Al_5FeSi_2(Sr, Ce)$
E	24.2	/	/	23.9	17.3	Bal.	Al_2Si_2Sr
F	21.4	3.1	/	4.6	48.9	Bal.	$(Al, Mg)_2Si_2(Sr, Ce)$

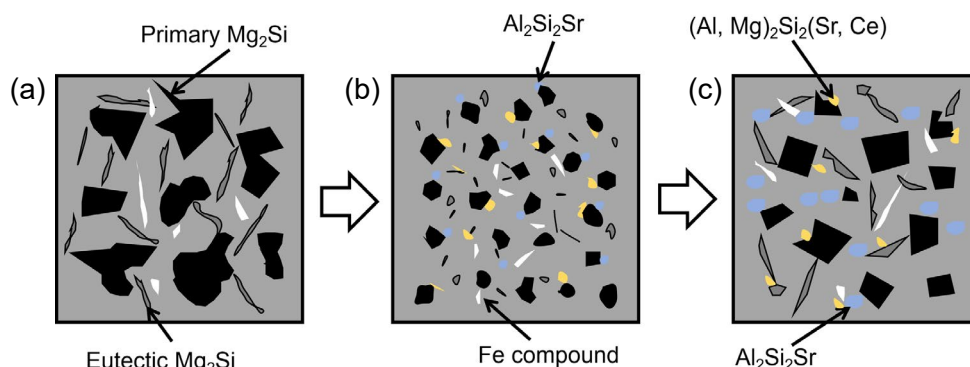


Fig. 13: Schematic diagram of modification processes under different Al-8Sr-8Ce contents: (a) 0wt.%; (b) 0.4wt.%; (c) 0.5wt.%

Moreover, Sr and Ce atoms preferentially adsorb on the {001} crystal planes of Mg_2Si phase and markedly inhibit the growth rate of {001} plane. Therefore, more {001} planes are retained in the final grain morphology, and primary Mg_2Si phase eventually transforms into a cubic structure surrounded by {001} planes, as depicted in Fig. 13(c).

5 Conclusions

In this work, the influences of varying Al-8Sr-8Ce modifier contents on the microstructure and mechanical properties of Al-15 Mg_2Si alloys were investigated, and the modification mechanism for primary and eutectic Mg_2Si phases was revealed.

(1) The addition of Al-8Sr-8Ce transforms the coarse and irregular blocky primary Mg_2Si morphology into a fine, regular polygonal one, while the coarse Chinese-script-like eutectic Mg_2Si phase changes into fibrous and granular shapes. The modification effect is gradually enhanced with increasing Al-8Sr-8Ce content until 0.4wt.%. When the content of Al-8Sr-8Ce surpasses 0.4wt.%, the refinement effect on primary and eutectic phases diminishes, and an obvious poisoning effect emerges.

(2) The incorporation of Al-8Sr-8Ce remarkably enhances the plasticity of Al-15 Mg_2Si alloys. As the content of the Al-8Sr-8Ce increases, the ultimate tensile strength and elongation of the Al-15 Mg_2Si alloys initially rise and then decline. The optimal mechanical properties are achieved at 0.4wt.% Al-8Sr-8Ce, where the ultimate tensile strength and elongation are increased by 7.6% and 60.0%, respectively, compared to those of the unmodified alloy.

(3) An appropriate amount of Al-8Sr-8Ce releases Sr and Ce atomic clusters and adsorbs on the surface of the Mg_2Si phases, thereby effectively restrains their growth. When the content of Al-8Sr-8Ce is excessive, a large number of $\text{Al}_2\text{Si}_2\text{Sr}$ preferentially form, which consumes a large number of active Sr and Ce atoms in the melt, and weakens the poisoning adsorption effect on Mg_2Si phases.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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