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Microstructure Evolution and Performance Improvement of Hypereutectic Al–Mg₂Si Metallic Composite with Ca or Sb

Min Zuo *, Boda Ren, Zihan Xia, Wenwen Ma, Yidan Lv and Degang Zhao

School of Materials Science and Engineering, University of Jinan, Jinan 250022, China; rbd18863515609@163.com (B.R.); xzh778888@163.com (Z.X.); mwwdeyouxiang@126.com (W.M.); lyd1169704770@163.com (Y.L.); mse_zhaodg@ujn.edu.cn (D.Z.)

* Correspondence: mse_zuom@ujn.edu.cn; Tel.: +86-531-82765317

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Abstract: In this article, the modification effects on Al–Mg₂Si before and after heat treatment were investigated with Ca, Sb, and (Ca + Sb). In comparison with single Ca or Sb, the samples with composition modifiers (Ca + Sb) had the optimal microstructure. The sample with a molar ratio for Ca-to-Sb of 1:1 obtained relatively higher properties, for which the Brinell hardness values before and after heat treatment were remarkably increased by 31.74% and 28.93% in comparison with bare alloy. According to differential scanning calorimetry analysis (DSC), it was found that the nucleation behavior of the primary Mg₂Si phase could be significantly improved by using chemical modifiers. Some white particles were found to be embedded in the center of Mg₂Si phases, which were deduced to be Ca₅Sb₃ through X-ray diffraction (XRD) and field-emission scanning electron microscope (FESEM) analyses. Furthermore, Ca₅Sb₃ articles possess a rather low mismatch degree with Mg₂Si particles based on Phase Transformation Crystallography Lab software (PTCLab) calculation, meaning that the efficient nucleation capability of Ca₅Sb₃ for Mg₂Si particles could be estimated.

Keywords: Al–Mg₂Si composite alloy; chemical modifier; microstructure; Brinell hardness; heterogeneous nucleation behavior

1. Introduction

Recently, aluminum matrix composites (AMCs), especially Mg₂Si-particle-reinforced aluminum matrix alloys, have attracted considerable attention due to their high specific strength, excellent wear, and anticorrosion resistance in structural components in the aerospace and automotive fields [1–3]. As an advanced intermetallic compound, Mg₂Si possesses excellent properties, including high hardness ($4.5 \times 10^9 \text{ N m}^{-2}$), low density ($1.99 \times 10^3 \text{ kg m}^{-3}$), low thermal expansion coefficient ($7.5 \times 10^{-6} \text{ K}^{-1}$), and a suitable elastic modulus (120 GPa), meaning it has been regarded as an intriguing candidate for use in structural applications [4,5]. As is known to all, the material performance is closely related to the configuration state [6,7]. Based on this, the question of how to prepare the controllable structural configuration of metallic alloys has been the focus of a number of studies.

As for Al–Mg₂Si alloys, the modification and refinement of Mg₂Si phases have become especially important topics, in which coarse primary Mg₂Si dendrites [8] and Chinese script eutectic Mg₂Si [9,10] would seriously weaken the mechanical properties of systems. Over the past few years, many researchers have developed various routes to achieve the optimization effect of the Mg₂Si phase, such as melt superheating [11], hot extrusion [12,13], ultrasonic melt treatment [14], rapid solidification [15], and heat treatment [16,17]. Besides these methods, chemical modifier treatments have been found to be much easier to operate with high efficiency, such as with Na [18], Sr [19], Be [20], Gd [21], La [22], and Y [23]. Farahany et al. [24] reported that a Bi additive also had a significant effect on the morphologies

of Al_2Cu (θ), Al_5FeSi (β), and $\text{Al}_5\text{Cu}_2\text{Mg}_8\text{Si}_6$ (Q) phases, in addition to an excellent modification effect on primary and eutectic Mg_2Si in Al – $20\text{Mg}_2\text{Si}$ – 2Cu composites. Alizadeh and Mahmudi [25] found that Sb could change the morphologies of Mg_2Si particles in Mg – 4Zn – 2Si alloys from Chinese script to more rounded edge types, resulting in better plasticity for shear deformation.

Based on the references above, it was found that most of chemical modifiers only work on one of the two Mg_2Si phases (primary Mg_2Si or eutectic Mg_2Si), with limited effect. Based on this, the complex modification treatment deserves more attention, owing to the considerable potential for the microstructural optimization of metallic alloys. Lv et al. revealed [26] that primary Mg_2Si particles were significantly refined from $95\text{ }\mu\text{m}$ to $10\text{ }\mu\text{m}$ with 2.0% Sb and 0.2% Bi, for which the Brinell hardness was increased up to 134.67 after heat treatment. Based on the rather low planar mismatch δ between $(111)_{\text{Mg}_2\text{Si}}$ and $(0001)_{\text{Mg}_3\text{Sb}_2}$ of 1.79%, Mg_3Sb_2 could act as the heterogeneous nucleation site for primary Mg_2Si , and with the cooperative absorption behavior of Bi on the growth front, the primary Mg_2Si dendrites would be obviously refined. Zha et al. [27] reported that an enhanced synergistic modification effect of Sb and Zr could be obtained for Al – $20\text{Mg}_2\text{Si}$ alloys. $\text{Mg}_3(\text{Sb}, \text{Si})_2$ particles could serve as the nuclei of primary Mg_2Si and Zr, further improving the refinement effect through the decrease of the solidification temperature interval of the primary particles. Researchers still need to do a lot of work to identify the interaction effects between chemical modifiers, such as promotion, inhibition, or no influence.

Recently, the complex additives of Ca and Sb into aluminum alloys containing Mg_2Si particles have drawn much attention. Yu et al. [28] revealed that CaSb_2 particles could serve as heterogeneous nucleation sites for primary Mg_2Si and Ca elements adsorbed on the growth front could restrict the growth rate of Mg_2Si . Due to the large electronegativity difference between Ca and Sb of 1.05, various Ca–Sb compounds could form. In this paper, the composite modifications of Ca and Sb with different atomic ratios in Al – $20\text{Mg}_2\text{Si}$ alloys were applied in this process. The effects of single Ca and Sb modifiers on the microstructure and mechanical properties of composites before and after heat treatment were also reported. The novel complex modification of Ca and Sb would open significant new opportunities for microstructural control and property enhancement of aluminum alloys containing Mg_2Si reinforcements.

2. Experimental Procedures

Commercially pure Al ingot (99.97%), pure Mg ingot (99.89%), and Al – 24Si master alloy were used as raw materials to prepare basic Al – 12.7Mg – 7.4Si alloys, which correspond to Al – $20\text{Mg}_2\text{Si}$ alloys (all compositions are in wt %, unless otherwise stated). Ca in the form of Al – 29Ca master alloy and pure Sb ingot (98.25%) was added into Al – $20\text{Mg}_2\text{Si}$ to investigate the interaction effects of modifiers.

Melt modifications of Al – $20\text{Mg}_2\text{Si}$ alloys were carried out as follows. By using an electrical resistance furnace (SG2–7.5–12, Longkou Electric Furnace Factory, Longkou, China), about 300 g of basic alloy was remelted in a graphite crucible ($\varnothing 94 \times 154\text{ mm}$) (Jinda Crucible Factory, Tianjin, China) at $780\text{ }^\circ\text{C}$ for 30 min. Subsequently, single modifier of Ca or Sb and a composite modifier (Ca + Sb) were added into the melt and mechanically stirred with a graphite rod for 10 min in order to obtain uniform dispersion. During the modification process, the melt temperature was monitored by a thermocouple and assisted by a K-model handset thermocouple (Wuxi Ruiwen Automation Instrument Co. LTD, Wuxi, China). Finally, the melt was poured into a permanent mold ($70 \times 35 \times 20\text{ mm}$) preheated to $200\text{ }^\circ\text{C}$. For the first group of modification treatments, the addition level of Ca was 0.15%. The second group of experiments was used to treat base alloys with various amounts of Sb (i.e., 0.23%, 0.46%, and 0.91%). Thirdly, the interaction influence of the composite modifier (Ca + Sb) on the microstructure of the base alloy was studied. In order to obtain more information, three molar ratios of Ca and Sb were evaluated, including 2:1 (0.15% Ca, 0.23% Sb), 1:1 (0.15% Ca, 0.46% Sb), and 1:2 (0.15% Ca, 0.91% Sb).

The Al – $20\text{Mg}_2\text{Si}$ samples were heat-treated following the T6 procedure, which involves treating the solution at $510\text{ }^\circ\text{C}$ for 4 h followed by water quenching and then artificial aging at $175\text{ }^\circ\text{C}$ for 8 h. Metallographic specimens were cut from the midsection of each sample and then mechanically ground and

polished through standard routines. In order to evaluate the microstructures of alloys, the average sizes of primary Mg_2Si particles were obtained from at least ten areas of specimen's metallograph, and from each area about ten primary Mg_2Si particles were chosen. The microstructural characterization of Al–20 Mg_2Si samples were determined with an optical microscope (4XC, Shanghai Caikon Optical Instrument Co. LTD, Shanghai, China) and a field-emission scanning electron microscope (FESEM) (QUANTA FEG250, FEI, Hillsboro, OR, USA) assisted by an energy-dispersive X-ray spectrometer (EDS) (INCA Energy X-MAX-50X, OIMS, Oxford, UK). The phase compositions of basic alloys were determined using X-ray diffraction (XRD) (D8 ADVANCE, Bruker, Germany) with $\text{Cu-K}\alpha$ in steps of 10° – 80° . Meanwhile, the scanning rate and acquisition step were $4^\circ/\text{min}$ and 0.02° (2θ), respectively. Brinell hardness values (HB) of Al–20 Mg_2Si composite alloys with different chemical modifiers were evaluated by a Brinell hardness tester with an applied load of 612.9 N pressed by a $\phi 5$ indenter (HBRVU-187.5, Shanghai Materials Testing Instrument Co. LTD, Shanghai, China). For each sample, the hardness values were obtained according to the average value from seven points. The melting and solidification behaviors of alloys were evaluated using differential scanning calorimetry (DSC) (DSC-404, Netzsch Inc., Selb, Germany) under argon flow protection within the range of 200–750 $^\circ\text{C}$ at a rate of 10 $^\circ\text{C/s}$. The possible orientation relationships between intermetallic compounds in this system were developed with the Phase Transformation Crystallography Lab software (PTCLab Version 1.19.0) [29].

3. Results and Discussion

Figure 1 shows the typical microstructures of Al–20 Mg_2Si composite alloys modified with 0.15% Ca. As a typical surface active element, Ca restricts the growth rate of the Mg_2Si phase, resulting in significant modification of particles. As the arrows indicate in Figure 1, primary Mg_2Si particles were refined from more than 100.0 μm to about 44.1 μm , with standard deviation of 4.7 μm . However, some coarse Mg_2Si dendrites were still detected with sizes up to 119.0 μm , as illustrated in Figure 1b. Furthermore, eutectic cell structures were obviously modified, as indicated by ellipses, with eutectic Mg_2Si particles changing to short rod-like structures and dots.

Figure 1. (a) typical microstructure of Al–20 Mg_2Si composites modified with 0.15% Ca; (b) partial enlarged drawing of this sample.

The typical microstructures of Al–20 Mg_2Si alloys modified with different addition levels of Sb are illustrated in Figure 2. It was found that Sb has an obvious influence on both phases of primary and eutectic structures. With the concentration of Sb increasing from 0.23% to 0.91%, the average sizes of primary Mg_2Si particles were 54.2 μm (standard deviation of 4.8 μm), 67.1 μm (standard deviation of 4.0 μm), and 46.7 μm (standard deviation of 4.2 μm), respectively. As indicated by circles in Figure 2a, Mg_2Si particles were obtained as corner-sharing octahedrons in three-dimensional spaces. Meanwhile, typical particles with four-petalled structures highlighted by circles were found, which were obtained from truncated octahedron Mg_2Si along (001) planes, as shown in Figure 2c. Due to the enrichment of Al atoms at the center of the {111} planes, the hopper structure of the Mg_2Si octahedron was formed.

With the addition of Sb increasing to 0.91%, the microstructure of the Al–20Mg₂Si composites was further optimized, with the eutectic cell structure being excellently modified.

Figure 2. Typical microstructures of Al–20Mg₂Si alloys with different addition levels of Sb: (a,b) 0.23%; (c,d) 0.46%; (e,f) 0.91%.

In comparison with modification efficiencies of single Ca and Sb, composite modifiers (Ca + Sb) with different molar ratios were added into Al–20Mg₂Si alloys, such as 2:1, 1:1, and 1:2 ratios. As indicated in Figure 3, it was found that with a molar ratio of Ca-to-Sb of 1:1, the sample possessed better modification and refinement efficiency than the other two samples. In addition to the rather fine spot-like eutectic Mg₂Si, primary Mg₂Si particles were refined to 27.7 μm with standard deviation of 2.9 μm. With a higher concentration of Sb, the eutectic structure tended to be coarser, as illustrated in Figure 3e,f. The mean size of primary Mg₂Si particles shown in Figure 3e was 55.8 μm. Furthermore, coarse flake-like eutectic Mg₂Si compounds were also observed in this sample.

Figure 3. Typical microstructures of Al-20Mg₂Si alloys modified by the complex modifier (Ca + Sb) with different molar ratios: (a,b) 2:1; (c,d) 1:1; (e,f) 1:2.

In order to get more information, the typical microstructures of these composite alloys after T6 heat treatment were studied and are shown in Figure 4. In comparison with single Sb addition, eutectic Mg₂Si compounds with a Ca modifier after heat treatment were finer. By modifying the compositions of Ca and Sb, the microstructures of the Al-Mg₂Si alloys after heat treatment were further optimized. As clearly illustrated in Figure 4c–e, the sharp edges of primary Mg₂Si polyhedrons became more rounded, with eutectic Mg₂Si phases transforming from flakes into fine spot-like shapes simultaneously. The sample modified with 0.15% Ca and 0.46% Sb (molar ratios for Ca-to-Sb of 1:1) possessed the optimal microstructure, meaning that mechanical properties of metallic alloys could be better predicted.

Figure 4. Typical microstructures of Al-20Mg₂Si alloys with Ca or Sb modifiers after heat treatment: (a) 0.15% Ca; (b) 0.46% Sb; (c) 0.15% Ca; 0.23% Sb (molar ratio of 2:1); (d) 0.15% Ca and 0.46% Sb (molar ratio of 1:1); (e) 0.15% Ca and 0.91% Sb (molar ratio of 1:2).

Figure 5 shows the Brinell hardness values of Al-20Mg₂Si alloys treated with different modifiers. It can be seen that with single addition of Ca and Sb, the Brinell hardness values of as-cast compositions were increased by 4.21%, 9.69%, 5.62%, and 16.0% respectively, compared with the basic alloy. After heat treatment, the Brinell hardness values of alloys were all improved to a certain extent. The samples with complex modifications obtained relatively higher hardness values, especially the one with a Ca/Sb molar ratio of 1:1. The Brinell hardness values of this sample before and after heat treatment were about 93.8 and 110.4, increasing by 31.74% and 28.93%, respectively, in comparison with the bare alloy.

Figure 5. Brinell hardness values of Al-20Mg₂Si alloys treated with different modifiers.

As we all know, the improvement of mechanical properties of metallic alloys is related to the optimization of the microstructure. With the addition of a chemical modifier, the solidification behavior of the Al-20Mg₂Si alloys might be influenced, resulting in the evolution of their microstructures. Figure 6 shows the differential scanning calorimetry (DSC) curves of Al-20Mg₂Si alloys with different chemical modifiers. As clearly indicated in Figure 6, the precipitation temperatures of primary Mg₂Si phases in alloys modified by Ca or Sb were in the range of 675–683 °C with a deviation of 2 °C, which were relatively higher values than that of the bare alloy. The increase in precipitation temperature of the primary phase implies the decrease of the required undercooling temperature, indicating that the nucleation behaviors of primary phases were significantly improved. Furthermore, the initial precipitation temperatures of eutectic Mg₂Si phases in these samples were 546, 545, 543, and 542 °C, respectively.

Figure 6. Differential scanning calorimetry (DSC) curves of Al-20Mg₂Si alloys with different modifiers: (a) bare alloy; (b) 0.15% Ca; (c) 0.91% Sb; (d) 0.15% Ca and 0.23% Sb.

The corresponding XRD patterns of Al–20Mg₂Si alloys before and after complex modifications of Ca and Sb are illustrated in Figure 7. In order to obtain clear diffraction peaks for possible compounds containing Ca or Sb, the concentrations of Ca and Sb were increased to about 1% and 3%, respectively, meaning that the molar ratio of Ca-to-Sb still remained at 1:1. Based on the XRD patterns, it could be found that besides Al and Mg₂Si phases, some weak diffraction peaks were detected, which were determined to be Ca₅Sb₃ compounds based on ICSD #002065. As the orange arrows indicate in Figure 7, the diffraction lines exhibited peaks at 32.46°, 34.42°, 35.68°, 49.47°, and 63.62°, corresponding to (222), (420), (203), (304), and (642) reflections of Ca₅Sb₃ (orthorhombic, Pnma, a = 1.250 nm, b = 0.951 nm, c = 0.829 nm) respectively. The formation of Ca₅Sb₃ compounds might be the reason for the excellent complex modification efficiency of Ca and Sb in Al–20Mg₂Si systems.

Figure 7. XRD patterns of as-cast Al–20Mg₂Si alloys: (a) bare sample; (b) modified sample.

The typical FESEM micrograph and corresponding EDS line scanning analyses along A–B are shown in Figure 8. It can be seen that there were some light grey particles embedded in the center of the primary Mg₂Si particle. According to the X-ray images for respective elements, enrichment of Ca and Sb elements in the area between the two dotted lines was observed, which was confirmed to be the heterogeneous nucleation site for the primary Mg₂Si phase during the solidification process. To obtain more details about this compound, a chemical composition analysis with an EDS test was carried out and is illustrated in Figure 9. From the FESEM image in Figure 9, the existence of light grey particles in the middle of primary Mg₂Si particles was proven. Based on the EDS results, the atomic ratio of Ca and Sb elements with light grey particle was about 1.95, which was relatively closed to 1.67 in the Ca₅Sb₃ phase. In accordance with the XRD analysis, this enrichment of Ca and Sb in the center of Mg₂Si provided further evidence of the heterogeneous nucleation effect of Ca₅Sb₃.

Figure 8. FESEM analysis of primary Mg_2Si in Al-20Mg₂Si alloys after modification by 0.15% Ca and 0.46% Sb: (a) microstructure; (b–f) the X-ray images for respective elements from A to B, including Al, Mg, Si, Ca, and Sb.

Figure 9. Typical FESEM analysis of Al-20Mg₂Si metallic alloy with Ca and Sb chemical modifiers: (a) microstructure; (b) the corresponding EDS analysis of the nucleus 1# in (a).

Yuan et al. [30] studied the microstructure refinement of Mg–Al–Zn–Si alloys with Sb and found that the morphological change of Mg₂Si was attributed to Mg₃Sb₂ as the nucleation nuclei. As a surface-active element, Ca elements could be adsorbed on the {111} and {100} planes of Mg₂Si particles, restricting the corresponding growth rates of these planes. Based on this, various stages of Mg₂Si-truncated octahedrons enclosed by {111} and {100} lattice planes would be formed. The electronegativity is a typical chemical characteristic, which indicates the ability of an atom to attract other electrons to itself. The larger the difference between the electronegativity parameters of two atoms, the higher the tendency for them to form compounds. In this Al–Mg₂Si system, Ca and Sb are likely to react with each other due to the large electronegativity difference of 1.05, resulting in the formation of various stoichiometric compounds [31]. Yu [32,33] investigated the crystallization behavior of primary Mg₂Si in composites with different Ca/Sb molar ratios. In their study, the total mass concentration of Ca and Sb was 0.5%, in which the addition levels of Ca and Sb were determined to be within the range of 0.05%–0.25% and 0.25%–0.45%, respectively. Furthermore, it was found that CaSb₂ and CaSi₂ could affect the nucleation process of primary Mg₂Si, resulting in the refinement of primary particles.

By using differential thermal analysis (DTA) and microstructure analysis, Niyazova et al. [34] first investigated the binary phase diagram of Ca–Sb and reported that three stable compounds could be formed, including Ca₃Sb₂, CaSb, and CaSb₃. Okamoto [35] further researched the Ca–Sb phase diagram based on new DTA data and negative formation enthalpies of Ca₁₁Sb₁₀ and Ca₅Sb₃. In addition, Martinez-Rippoll and Brauer [36] deduced the Ca₃Sb₂ phase to be the stoichiometry of Ca₅Sb₃, and Leon-Escamilla and Corbett [37] refined the crystal structure of Ca₅Sb₃. Qin et al. [38] studied the thermodynamic modeling of the Ca–Sb system by using first-principles calculations. According to their research, the thermodynamic behaviors of different compounds in the Al–Mg–Si–Ca–Sb system could be discussed as follows. According to XRD and EDS analyses, the nucleation nuclei embedded in primary Mg₂Si particles were deduced to be Ca₅Sb₃, which could be formed through the following Equation (1):

The standard Gibbs free energy change ΔG could be obtained through the corresponding Equation (2):

$$\Delta G = -618918 + 207.28T \quad (2)$$

in which T is the temperature of the liquid melt in degrees Celsius. When the system temperature changed from 700 to 1000 °C, the ΔG values fell in the range of –411 to –473 kJ/mol, which proved the feasibility of this reaction due to the large negative values. In comparison with the formation

reaction of CaSb_2 [32], the precipitation of Ca_5Sb_3 possesses a much lower ΔG value, meaning a greater tendency for the formation of Ca_5Sb_3 .

According to the edge-to-edge matching model [39,40], the Ca_5Sb_3 phase could act as a potential heterogeneous nucleation site for Mg_2Si particles due to the low mismatch degree, which was obtained using Phase Transformation Crystallography Lab software (PTCLab). The detailed orientation relationships between Ca_5Sb_3 and Mg_2Si phases are listed in Figure 10. Based on the calculations, the interatomic spacing misfit between $\langle 100 \rangle_{\text{Ca}_5\text{Sb}_3}$ and $\langle 01\bar{1} \rangle_{\text{Mg}_2\text{Si}}$ was rather low at 0.08%. Meanwhile, the corresponding interplanar spacing mismatches between $\{050\}_{\text{Ca}_5\text{Sb}_3}/\{400\}_{\text{Mg}_2\text{Si}}$ and $\{002\}_{\text{Ca}_5\text{Sb}_3}/\{111\}_{\text{Mg}_2\text{Si}}$ were merely 2.10% and 4.80%, respectively. From this, the efficient nuclear capability of Ca_5Sb_3 for Mg_2Si particles could be estimated, which was further confirmed by the FESEM results shown in Figures 8 and 9.

Figure 10. The corresponding interatomic spacing and interplanar spacing misfits between Ca_5Sb_3 and Mg_2Si phases.

With the co-modification of Ca and Sb, the mechanical properties of Al– Mg_2Si composite alloys were improved, which were attributed to the optimization of the microstructure. As for polycrystalline alloys, the effects of grain size on mechanical properties could be described by the Hall–Patch Equation (3). Based on the Hall–Patch model:

$$H = H_0 + kD^{-1/2} \quad (3)$$

where H_0 is the hardness of the bulk material, k is the constant in the relationship with the material characteristic, and D is the average grain size [41,42]. With the heterogeneous nucleation sites provided by Ca_5Sb_3 , coarse primary Mg_2Si dendrites were changed into fine particles. Additionally, the eutectic structure was also efficiently modified due to the existence of Ca. Through the efficient refinement of primary Mg_2Si and modification of the eutectic structure, the hindrance ability of the grain boundaries as the obstacles for crack propagation would be significantly improved, resulting in the promotion of mechanical properties.

4. Conclusions

In summary, a novel precipitation behavior control method with (Ca + Sb) was applied for microstructural control and performance improvement of Al– Mg_2Si alloys. The modification mechanism of the complex modifier (Ca + Sb) in this alloy was also investigated.

- In comparison with single Ca or Sb modifiers, the optimum modification effect for the Al– Mg_2Si alloy was obtained through the composite addition of (Ca + Sb), especially for the alloy with 0.15%

Ca and 0.46% Sb (molar ratio of 1:1), which possessed an optimal microstructure configuration and mechanical properties;

- Through FESEM and XRD analyses, Ca_5Sb_3 compounds were observed in the center of the primary Mg_2Si particles. Furthermore, the formation feasibility of Ca_5Sb_3 was also proven by thermodynamic calculation;
- According to DSC analysis, the precipitation of primary Mg_2Si phases in Ca- or Sb-modified alloys was in the range of 675–683 °C, meaning that the precipitation behavior could be improved;
- Ca_5Sb_3 has a rather low mismatch degree with Mg_2Si particles according to calculations using Phase Transformation Crystallography Lab software (PTCLab). The interatomic spacing misfit between $\langle \bar{1}00 \rangle_{\text{Ca}_5\text{Sb}_3}$ and $\langle 01\bar{1} \rangle_{\text{Mg}_2\text{Si}}$ was rather low at 0.08%. Meanwhile, the corresponding interplanar spacing mismatches between $\{050\}_{\text{Ca}_5\text{Sb}_3}/\{400\}_{\text{Mg}_2\text{Si}}$ and $\{002\}_{\text{Ca}_5\text{Sb}_3}/\{111\}_{\text{Mg}_2\text{Si}}$ were merely 2.10% and 4.80%, respectively;
- Based on these findings, the efficient nucleation behavior of Ca_5Sb_3 for Mg_2Si particles could be estimated, resulting in the improvement of the microstructure and mechanical properties of composite alloys.

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