Modification of Mg$_2$Si Phase Morphology in Mg-4Si Alloy by Sb and Nd Additions

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We reported the effects of compound modification with Nd and Sb on the microstructure evolution and mechanical properties of Mg$_2$Si particles. The characterization results showed that adding 1.0 wt.% Sb and 1.0 wt.% Nd to the alloy can effectively change the morphology of Mg$_2$Si particles. The primary Mg$_2$Si particles changed from coarse dendrites to regular polygons, and the average particle size decreased from 78.3 to 6.5 μm. Meanwhile, the Chinese eutectic Mg$_2$Si became small short fiber. The experimental results showed that the Nd$_4$Sb$_3$ phase could be formed after adding 1.0 wt.% Sb and 1.0 wt.% Nd to the alloy. The Nd$_4$Sb$_3$ phase could act as the heterogeneous nucleation core of Mg$_2$Si phase, which increased the nucleation rate of Mg$_2$Si and improved the morphology of Mg$_2$Si particles. The mechanical properties test found that the tensile properties and Brinell hardness of the alloy were improved with Sb and Nd alloyed. After adding 1.0 wt.% Sb and 1.0 wt.% Nd to the alloy, the ultimate tensile strength increased from 113 to 184 MPa, the elongation increased from 2.23 to 4.61%, and the Brinell hardness increased from 65.45 to 87.32 HB.

Keywords compound modification, magnesium alloy, mechanical property, Mg$_2$Si phase, microstructure

1. Introduction

Lightweight magnesium alloys have broad applications in various fields including electronic, aerospace (Ref 1, 2), and automation because of their high specific strength, high stiffness, relatively low density, good electrical conductivity, and excellent machinability (Ref 3, 4). However, one of the disadvantages of magnesium alloys is that the high-temperature mechanical properties of this material are somewhat poor, and this greatly limits broader industrial applications (Ref 5, 6).

Recent studies have reported methods to improve the heat-resistance problem of magnesium alloys such as microalloying (Ref 7), deformation strengthening (Ref 8), and second phase strengthening (Ref 9). Apparently, introducing Mg$_2$Si particles into the alloy was the most widely valuable because they are convenient and do not require complicated equipment. Furthermore, the Mg$_2$Si phase has some excellent characteristics such as low density (1.88 g/cm$^3$), high melting point (1087 °C), high hardness (HV 460), high elastic modulus (120 GPa), high elastic modulus (120 GPa), and low thermal expansion coefficient (7.5 × 10$^{-6}$ K$^{-1}$) (Ref 10); the Mg$_2$Si phase can be stably present at high temperatures and enhance the mechanical properties of the material. Thus, the Mg$_2$Si phase is an ideal reinforcement phase for magnesium alloys.

However, many rough dendritic primary Mg$_2$Si and Chinese eutectic Mg$_2$Si are produced during the solidification of Mg-4Si alloy throughout the magnesium matrix. These features negatively affect the physical properties of magnesium alloys. In view of this, optimizing the morphology and structure of Mg$_2$Si particles is necessary to improve the alloy performance.

There have been many studies demonstrating that the morphology of Mg$_2$Si can be modified upon adding different modifiers. Previous studies have indicated that coarse dendritic primary Mg$_2$Si particles were changed to regular polygons after adding Sb (Ref 11, 12), Nd (Ref 13, 14), Ba (Ref 15), or P (Ref 10, 16) to Mg-Si alloys: The modification mechanism of these elements can be concluded as the formation of a heterogeneous nucleation core of the Mg$_2$Si phase. In addition, the Y (Ref 17, 18), KBF$_4$ (Ref 19), and Bi (Ref 20) can also modify the coarse dendritic primary Mg$_2$Si because they inhibit the growth of Mg$_2$Si phase. Furthermore, the combination of two modifiers such as Ba-Sb (Ref 21), Sr-Sb (Ref 22), and Ca-Sb (Ref 23) can alert the coarse dendritic primary Mg$_2$Si as well. However, the size of most modification Mg$_2$Si particles is larger than 20 μm, and thus, we need more effective modifiers to further refine the primary Mg$_2$Si particles.

Previous studies have found that Sb transformed coarse dendritic primary Mg$_2$Si into regular polygonal particles by increasing the number of heterogeneous nucleation sites (Ref 11). Nd is also an effective modifier for Mg$_2$Si phase. Therefore, Sb and Nd would have synergistic modification effects. Thus, Nd and Sb were added to the Mg-4Si alloys to see the modification effect, and the objective of this work is to find an effective compound modifier and to evaluate the effect of Nd-Sb addition on the microstructure of Mg-4Si alloys, as well as to explore the mechanism of Nd and Sb compound modification.
2. Experimental Procedures

First, Mg ingot (\(> 99.9 \text{ wt.}\%\)) and Si ingot (\(> 99.8 \text{ wt.}\%\)) should be available for the preparation of Mg-4Si alloy. 1100 g pure Mg ingots were melted to 700 °C, and 40 g fine silicon particles were added into the melt solution after the pure magnesium is melted. And Mg ingot was added more due to Mg burned easily. A small amount of covering agent was added to the surface of the molten metal during the smelting process to protect the molten metal. This was held at 700 °C for 20 min and stirred evenly after slag removal. The molten magnesium solution can be poured into a cast iron mold preheated at 250 °C. This is the basis of subsequent experiments.

A previous study showed that the best modification effect was achieved after adding 1.0 wt.% Sb to the Mg-based alloy when adding a single modification element Sb (Ref 21). In this case, the only variable in the experiment was the difference in Nd content. The 1.0 wt.% Sb was added to the re-melted Mg-4Si alloys, and different amounts of Mg-30Nd alloy were added to the re-melted Mg-4Si alloys. The molten metal was kept at 700 °C for 20 min. After stirring, the molten metal was poured into a cast iron mold preheated at 250 °C to obtain the samples: This produced bars 20 mm in diameter. Table 1 shows the designed ratios of the Nd and Sb contents of the prepared ingots.

All metallographic samples in this experiment were taken from the same position of ingot. The samples were finely ground with different meshes of sandpaper, polished with a diamond spray polish, and then etched with 0.1% acetic acid. diamond spray polish, and then etched with 0.1% acetic acid. After that, OLYMPUS-PMG3 optical microscope (OM) was used to observe the microstructure of the samples. Finally, AxioVision software was used to calculate the average size and density of Mg2Si particles. The calculation process is as follows (Ref 24):

\[
\text{Mean size} = \frac{1}{m} \sum_{j=1}^{m} \left( \frac{1}{n} \sum_{i=1}^{n} L_i \right)
\]

\[
\text{Mean density} = \frac{1}{m} \sum_{j=1}^{m} \left( \frac{1}{n} \sum_{i=1}^{n} D_i \right)
\]

where \(L_i\) was the size of a single Mg2Si particle and \(D_i\) is the density of Mg2Si particles, respectively. Term \(n\) was the amount of Mg2Si particles counted in this area at 71,300 \(\mu\text{m}^2\), and \(m\) was the number of the measurement areas. A JSM-6610 scanning electron microscope (SEM) was used to analyze the microscopic appearance and element composition of the second phase. Nanoscale second phase particles were observed and analyzed by transmission electron microscopy (TEM), and the samples were prepared by focusing particle beams. Titan G2 60-300 model was used for TEM observation at 300 kV. The elemental composition of the second phase was obtained by mapping analysis, and the crystal structure of the second phase was determined by selected area electron diffraction.

Tensile test bars were prepared in accordance with the ASTM B557 M-02a standard, and the gauge length was set to 30 mm, and the cross section diameter was 6 mm. This tensile test was performed by use of a CMT5504 universal testing machine controlled by computer in the constant crosshead speed of 1 mm/min, and each sample was tested five times at room temperature. The fracture surface was observed by SEM, and the average ultimate tensile strength (UTS) and elongation were calculated. The hardness of samples was tested by use of a Brinell hardness tester (HBE-D3000A) under 2450 N load, with 15 s residence time and \(\Phi\) 2.5 indenter. The present values in this paper are the average value of five random different positions.

3. Experiment Results and Discussion

3.1 Phase Analysis

Figure 1 shows the XRD examination results of Alloy 1 to 5, and it is clear that Mg2Si phase and Mg phase were observed in the Mg-4Si alloy, indicating that Mg2Si phase was formed during the solidification.

3.2 Microstructure Evolution

Figure 2 shows the microstructure of Mg-4Si alloys under different Nd and Sb addition values. The microstructure of unmodified Mg-4Si alloy (Fig. 2a) is composed of white \( \alpha\)-Mg matrix, and Chinese eutectic Mg2Si and coarse black primary Mg2Si dendrites had a size of about 78 \(\mu\text{m}\). According to the binary phase diagram of magnesium–silicon, dendritic primary Mg2Si is first precipitated during the solidification process and then precipitates Chinese character eutectic Mg2Si.

By adding 1.0 wt.% Sb to the Mg-4Si alloy, the morphology of primary Mg2Si particles can significantly change from coarse dendrites to regular polygons (Fig. 2b) and the size reduced to about 20 \(\mu\text{m}\), while the amount of Chinese eutectic Mg2Si was

![Fig. 1 XRD patterns of alloy 1, alloy 2, alloy 3, alloy 4, alloy 5](image_url)

| Alloy number | 1   | 2   | 3   | 4   | 5   |
|--------------|-----|-----|-----|-----|-----|
| Sb content, wt.% | 0   | 1.0 | 1.0 | 1.0 | 1.0 |
| Nd content, wt.%  | 0   | 0.5 | 1.0 | 2.0 |
reduced. To better modify the refined primary Mg$_2$Si particles, increasing ratios of Nd were added to the 1.0 wt.% Sb metamorphic Mg-4Si alloy. The addition of Nd makes the average particle size decrease significantly, and the particle size of primary Mg$_2$Si increases slightly when the addition amount of Nd is up to 1.0 wt.%.

Figure 2(c) shows that after adding 1.0 wt.% Sb and 0.5 wt.% Nd, the number of primary Mg$_2$Si particles decreased with increasing eutectic Mg$_2$Si content, and the particle size changed slightly. Figure 2(d) shows that with the increase in Nd content, the average size of primary Mg$_2$Si particles decreased significantly upon addition of 1.0 wt.% Nd. The Mg$_2$Si particles have the best polygon, and the average particle size obtained by OM is 6.5 μm. However, the amount of primary Mg$_2$Si particles decreased, and the size became larger when the Nd was continuously added to the alloy (Fig. 2e). At the same time, the changes in the average size and density of the primary Mg$_2$Si particles are plotted in Fig. 3: the density of the primary Mg$_2$Si particles increased with decreasing size. Figure 4 shows the magnified SEM observation on the alloys with different Sb and Nd addition, indicating that the Chinese-script eutectic Mg$_2$Si was significantly refined after the compound modification of Sb and Nd, and the amount of the eutectic Mg$_2$Si reduced with the addition of Nd up to 1.0 wt.%.

![Fig. 2](image1.png)

**Fig. 2** Microstructures of Mg-4Si alloy (a) without modification and with modification of (b) 1.0 Sb, (c) 1.0 Sb-0.5 Nd, (d) 1.0 Sb-1.0 Nd, and (e) 1.0 Sb-2.0 Nd (wt.%)

![Fig. 3](image2.png)

**Fig. 3** Average size of primary Mg$_2$Si particles

### 3.3 Modification Mechanism

The results show that the addition of 1.0 wt.% Sb and 1.0 wt.% Nd has obvious compound modification effect on the primary Mg$_2$Si phase of Mg-4Si alloy. The modification mechanism of Nd and Sb on Mg-4Si alloy was studied by
SEM. There were white cores in the middle or edge of the modified Mg2Si phase (Fig. 5a and b), which could act as a heterogeneous nucleation core of the primary Mg2Si particles. Figure 5(a) and (c) shows the SEM images and EDS analysis of the 1 wt.% Sb modified Mg-4Si alloy. Figure 5(a) shows that there are some white cores in the primary Mg2Si particles. There is a point sweep of the white cores in Fig. 5(a), which reveals that the constituent elements of the white cores are Mg, Si, and Sb. Previous studies showed that the Mg3Sb2 phases can be formed in the Mg-Si alloy after adding Sb. These acted
as nucleation sites for the primary Mg$_2$Si particles (Ref 25). It can be seen from Fig. 5(a) that the Mg$_3$Sb$_2$ phase is too small, and the nucleation rate of the primary Mg$_2$Si was minimally improved, so the average size of the primary Mg$_2$Si particles was about 20 µm.

Figure 5(b) shows that the amount of white cores in the primary Mg$_2$Si particles obviously increased after adding 1 wt.% Sb and 1 wt.% Nd to the Mg-4Si alloy. Meanwhile, the average size of primary Mg$_2$Si particles decreased to 6.5 µm and was evenly distributed in the matrix; eutectic Mg$_2$Si changed from Chinese characters to small short fibers. The point sweep of the white core in the primary Mg$_2$Si particles in Fig. 5(d) reveals that there are Mg, Si, Sb, and Nd on the white cores—the possible intermetallic compounds between these elements include Mg$_3$Sb$_2$, NdSi$_2$, and Nd$_4$Sb$_3$.

The element composition of the core of the primary Mg$_2$Si particles will be confirmed in a future TEM study. Figure 6 shows a high-power bright TEM image with mapping analysis. The bright image (Fig. 6a) shows a dark phase that we think is the α-Mg phase, and there is also a white phase inside the Mg$_2$Si particles that is heterogeneous nucleation core of the primary Mg$_2$Si particles. The mapping analysis shows that there are Nd and Sb enrichments in the white core of the primary Mg$_2$Si particles (Fig. 6e and f). The white intermediate phase is likely a compound of Nd and Sb (Ref 26).

Figure 7 shows the high-power bright-field TEM image and selected area electron diffraction image of Mg-4Si alloy with 1.0 wt.% Sb and 1.0 wt.% alloyed Nd. The SAD pattern was collected from at least two regional axes by tilting the sample to determine the crystal structure (Ref 27). The target and selected area electron diffraction aperture were adjusted, and the intermetallics of Nd and Sb nanoparticles were studied. The area circled by the solid circle of 100 nm is the area of the selected area electron diffraction analysis. The SAD patterns were analyzed, and the results suggest that the core of the primary Mg$_2$Si consists of a Nd$_4$Sb$_3$ phase and a zone axis $A = [131]$. Through these, the Nd$_4$Sb$_3$ phase has a cubic structure with lattice parameters of 0.9406 nm and belongs to

Fig. 6 (a) TEM bright image; EDS elemental mappings of (b) Mg; (c) Si; (d) Sb; and (e) Nd
and Si. Therefore, Nd and Sb combine to form Nd$_4$Sb$_3$ phases than the electronegativity difference between Mg and Sb, or Nd electronegativity difference between Nd and Sb is much larger and Si is 1.14, 2.05, 1.31, and 1.98, respectively. Obviously, the compound formation. The electronegativity of Nd, Sb, Mg,ences lead to higher attraction and greater potential for
electrons. A higher electronegativity implies a stronger ability
to attract electrons. In general, larger electronegativity differ-
ences are effective to change the morphology of Mg$_2$Si particles. This method is simple and efficient. The modification mechanism of the addition of Sb or Nd is to form a kind of heterogeneous nucleation core of Mg$_2$Si particles, and it will increase the nucleation rate (Ref 11, 14). For example, the Mg$_3$Sb$_2$ phase will be formed, while Sb was added to the Mg-Si alloys (Ref 12). These are the nucleation centers of primary Mg$_2$Si particles. When Nd is added to the alloy, NdSi$_2$ can play a similar role to the Mg$_2$Si particles (Ref 14). However, when Sb and Nd were added at the same time, no Mg$_3$Sb$_2$ or NdSi$_2$ particles were observed. In contrast, only Nd$_4$Sb$_3$ particles were detected in the newly formed phase; no other intermediate phase was observed. This can be explained by the differences in electronegativity of different atoms.

Electronegativity is a measure of an atom’s ability to attract electrons. A higher electronegativity implies a stronger ability to attract electrons. In general, larger electronegativity differences lead to higher attraction and greater potential for compound formation. The electronegativity of Nd, Sb, Mg, and Si is 1.14, 2.05, 1.31, and 1.98, respectively. Obviously, the electronegativity difference between Nd and Sb is much larger than the electronegativity difference between Mg and Sb, or Nd and Si. Therefore, Nd and Sb combine to form Nd$_4$Sb$_3$ phases instead of Mg$_3$Sb$_2$ phases and NdSi$_2$ phases as other studies have done.

In order to investigate whether the Nd$_4$Sb$_3$ phase can be used as the heterogeneous nucleation core of the Mg$_2$Si phase, the lattice mismatch between Nd$_4$Sb$_3$ and Mg$_2$Si was calculated according to Bramfitt theory. The Bramfitt theoretical calculation formula is shown as follows (Ref 25):

$$\varphi_{(hkls)}^{(hkls)} = \frac{1}{3} \sum_{i=1}^{3} \left| d_{[uvw]}^i \cos \theta - d_{[uvw]}^i \right|$$

(Eq 3)

Here, (hkls) is the low-index crystal plane of the heterogeneous substrate, and [uvw]$_n$ is the low-index crystal orientation in the (hkls)$_n$ plane. Term (hkls)$_n$ is the low-index crystal plane of the new crystal nucleus, and [uvw]$_n$ is the low-index orientation in the (hkls)$_n$ plane. Terms $d_{[uvw]}^i$ and $d_{[uvw]}^i$ are atomic spatial distances along the [uvw]$_n$ and [uvw]$_n$ orientations, and $\theta$ is the angle between [uvw]$_n$ and [uvw]$_n$ orientations ($\theta < 90^\circ$).

Through the study of Bramfitt theory, the energy at the boundary of the heterogeneous nucleation core and the Mg$_2$Si phase affects the formation of the heterogeneous core. This is mainly related to the energy at the contact surface, and the key to the formation of the heterogeneous nucleation core is that the lattice mismatch of the contact surface is less than 15%.

Figure 9 shows the (001) crystal plane of the Mg$_2$Si phase and the (211) crystal plane of the Nd$_4$Sb$_3$ phase. The planar mismatch of some possible crystallographic orientations for Mg$_2$Si nucleation on the Nd$_4$Sb$_3$ particles was calculated according to Fig. 9 and Bramfitt theory. Table 2 shows that the disregistry reaches 9.33% when the orientation relationship between Nd$_4$Sb$_3$ and Mg$_2$Si is (211)$_{Nd4Sb3}$//(001)$_{Mg2Si}$. From Bramfitt’s theory, the mismatch between two-phase planes is less than 15%, and one phase can act as a heterogeneous nucleation point for the other phase. Therefore, the Nd$_4$Sb$_3$ phase can be used as a heterogeneous nucleus of primary Mg$_2$Si phase. The formation of a large number of fine Nd$_4$Sb$_3$ particles improved the nucleation rate of primary Mg$_2$Si particles. Therefore, during solidification, the core of the primary Mg$_2$Si increases and is evenly distributed in the matrix. The primary Mg$_2$Si particles do not grow into dendritic crystals, but rather become a small regular polygon.

The results show that the average size of the primary Mg$_2$Si particles is much smaller than that of the single Nd or Sb element after adding Nd and Sb at the same time. This is due to that adding 1.0 wt.% Nd and 1.0 wt.% Sb to Mg-4Si alloy can form a Nd$_4$Sb$_3$ phase, which is the heterogeneous nucleation
center of primary Mg$_2$Si particles. Therefore, the nucleation rate of the primary Mg$_2$Si phase is greatly increased, and the morphology of Mg$_2$Si changes from a coarse dendritic shape to a regular polygon. However, as the Nd content exceeds 1.0 wt.%, the primary Mg$_2$Si particles begin to grow slightly larger. This is because of the Nd-Sb binary phase diagram. The Nd$_4$Sb$_3$ phase can be formed when the contents of Nd and Sb are close to each other. With increasing addition of Nd, the Nd$_4$Sb$_3$ phase can finally be formed, but it cannot act as a heterogeneous nucleation site for the primary Mg$_2$Si particles. Therefore, the nucleation rate of primary Mg$_2$Si decreases and the primary Mg$_2$Si particles become much larger. Meanwhile, the amount of Chinese eutectic Mg$_2$Si increases sharply with much more alloyed Nd. This is called the over-modification phenomenon.

### 3.4 Mechanical Properties

The tensile mechanical properties and hardness of different samples were tested to investigate the effect of adding different amounts of modifier on the mechanical properties of Mg-4Si alloy (Fig. 10 and 11).

#### 3.4.1 Hardness

The change of hardness can be found in Fig. 10 of Mg-4Si alloy after adding different amounts of Nd and Sb. Figure 10 shows that the Brinell hardness of the unmodified Mg-4Si alloy is at least HB 65.45, and the Brinell hardness value of the alloy first increases and then decreases upon addition of different amounts of modifiers. The maximum value was HB 89.17, and this was achieved upon modification of 1.0 wt.% Sb and 1.0 wt.% Nd. These results indicate that the hardness value of the Mg-4Si alloy is related to the morphology of the primary Mg$_2$Si particles. The fine regular polygonal particles contribute to the improvement of the hardness. This is because the stress at the contact point of the Mg$_2$Si particles with the magnesium matrix is reduced after deformation. Thus, it is difficult to initiate cracks at the interface between the primary Mg$_2$Si particles and magnesium matrix. Thus, the hardness of the alloy increased via 1.0 wt.% Sb and 1.0 wt.% Nd modification.

#### 3.4.2 Tensile Properties and Fracture Characteristics

Tensile properties of Mg-4Si alloy modified by different content Sb and Nd are shown in Fig. 11. The ultimate tensile strength in the experiment is raised from 113.24 to 175.38 MPa.
when the Mg-4Si alloy was modified by adding 1.0 wt.% Nd and 1.0 wt.% Sb. With the elongation increases from 2.23% to 4.61%, it is clear that improvement of the mechanical properties of the alloy is closely related to the morphology of the Mg2Si-reinforced phase. This is because of the thermal expansion coefficient between the matrix and the reinforcing phase and the Griffith formula.

An improved coefficient of thermal expansion (CTE) mismatch can increase the ultimate tensile strength of the Mg-4Si alloy (Ref 29). Due to the large difference in the CTE between α-Mg and Mg2Si reinforcement phase, there is a relatively large residual stress between Mg2Si and magnesium matrix during alloy smelting. Residual stress concentration at the grain boundary produces many high-density dislocations between the magnesium matrix and the Mg2Si reinforcing phase, and the dislocation motion of the material becomes more difficult resulting in an increase in the strength of the material. The CTE mismatch is related to the size and shape of the reinforcing phase particles (Ref 30). The eutectic Mg2Si was still refined after adding 1.0 wt.% Sb and 1.0 wt.% Nd to the Mg-4Si alloy; thus, the alloys were further strengthened with the addition of Nd up to 1.0 wt.%.

The other strengthening mechanism is related to the size of the primary Mg2Si particles; the relationship between the particle diameter (d) and the fracture stress (σc) was demonstrated by the Griffith equation as follows (Ref 12):

\[
\sigma_c = k_c d^{-0.5}
\]

(Eq 4)

Here, \(k_c\) is the fracture toughness of the particle, and d is the diameter of the particle. Griffith’s theory states that the fracture stress of the test alloy increases with decreased particle diameter. The primary Mg2Si particle size decreases signifi-

![Fig. 11 Effect of different contents of Sb and Nd on the tensile properties of Mg-4Si alloy](image1)

![Fig. 12 Representative micrograph of a fractured surface on the Mg-4Si alloy: (a) alloy 1; (b) alloy 2; (c) alloy 3; (d) alloy 4; (e) alloy 5](image2)
cantly in the Mg-4Si alloy with the addition of 1.0 wt.% Nd and 1.0 wt.% Sb. This means that more stress is needed to break the Mg-4Si alloy after 1.0% Nd and 1.0% Sb addition. This improves the UTS and elongation values.

The typical fracture surface of the test alloy after adding different amounts of Nd and Sb to the alloys is shown in Fig. 12. Figure 12(a) shows that the cross section of the unmodified Mg-4Si alloy consists of a flat tearing surface on the Mg$_2$Si particles. These tearing surfaces are irregularly shaped with cracks. This is attributed to the presence of coarse dendritic primary Mg$_2$Si and Chinese eutectic Mg$_2$Si in the unmodified Mg-4Si alloy. The sharp edges of the unmodified primary Mg$_2$Si particles generate a large amount of stress when they are in contact with the magnesium matrix, and these particles are concentrated at the grain boundaries. The crack is generated under a tensile load, and this crack expanded along the edge of the unmodified primary Mg$_2$Si and eutectic Mg$_2$Si, which will reduce the strength and elongation of the alloy.

Figure 12(b–e) shows the fracture surface of the alloy with different Nd and Sb addition. It can be seen that the smaller the particles falling off, the less obvious the crack growth is. The Mg$_2$Si phase prefers to act as the potential crack initiation site, so the refined Mg$_2$Si phases could decrease the stress concentration and prevent the crack initiation (Ref 31, 32). This indicated that the ultimate tensile strength improved due to that the morphology of primary Mg$_2$Si was changed from coarse dendrite to regular polygon by the addition of Sb and Nd. Meanwhile, the morphology of eutectic Mg$_2$Si was changed from Chinese character to small short rod. Small fine polygonal Mg$_2$Si particles are benefited to prevent the generation and development of cracks. Therefore, the ultimate tensile strength and elongation of the alloy have been greatly improved.

4. Conclusions

(1) The effect of the addition of Sb and Nd compound modification is as follows: The morphology of primary Mg$_2$Si particles changes from coarse dendrite to regular shaped polygon, and the average size of the primary Mg$_2$Si particles decreased to 6.5 µm from 78 µm after adding 1.0 wt.% of Sb and 1.0 wt.% Nd. Furthermore, the amount of eutectic Mg$_2$Si reduced with addition of Nd elements up to 1.0 wt.%. The Chinese-shaped eutectic Mg$_2$Si is metamorphosed into a small short rod shape distributed in matrix. Therefore, the simultaneous addition of Sb and Nd is much better than the addition of Sb or Nd alone.

(2) The Nd$_4$Sb$_3$ phase appeared in the core of the primary Mg$_2$Si particles after adding 1.0 wt.% Nd and 1.0 wt.% Sb to the Mg-4Si alloy. The crystal lattice mismatch between Nd$_4$Sb$_3$ and Mg$_2$Si was 9.33% (less than 15%), and thus, the Nd$_4$Sb$_3$ phase can be used as heterogeneous nucleation core of primary Mg$_2$Si particles. Therefore, the nucleation rate of the Mg$_2$Si phase is increased, and the primary Mg$_2$Si particles become regular and uniformly distributed in the magnesium matrix.

(3) The hardness and tensile strength of the alloy increased with the modification of Sb and Nd. The Brinell hardness of the alloy increased from HB 65.45 to HB 89.17. In addition, the mechanical properties showed that the UTS value increased from 113.24 to 175.38 MPa, and the elongation changes from 2.23 to 4.61%. These are attributed to the compound modification for primary and eutectic Mg$_2$Si particles.

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Conflict of interest

The authors declare that they have no conflict of interest.

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