Microstructures and High-Temperature Properties of Sm-Modified Mg-4Al-4RE Alloy

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Abstract: The effect of Sm on the microstructure and tensile properties of Mg-4Al-4 (La, Ce) alloy was studied. The Mg-4Al-4 (La, Ce) alloy was mainly composed of α-Mg and Al11(La, Ce)3. With the addition of Sm, a new phase of Al2(La, Ce, Sm) was revealed in the alloy. The results showed that at room temperature (RT), after Sm addition, the ultimate tensile stress and the elongation decreased, while the yield stress increased slightly; the elongation increased with the Sm addition and the yield stress was basically the same, but the ultimate tensile stress decreased at an elevated temperature of 150°C. The change in the mechanical properties of the alloy was mainly related to the change in microstructure and phase. With the increase in Sm content, the volume fraction of Al2(La, Ce, Sm) phase increased and the Al11(La, Ce)3 eutectic volume fraction decreased significantly, which led to a change in the mechanical properties of the alloy. The 1 wt.%Sm-addition alloy exhibited greater elongation than the Sm-free alloys.

Keywords: Mg-4Al-4 (La, Ce); samarium; high temperature performance

1. Introduction

Magnesium alloy is the lightest metal alloy structural material in practical application; it is widely used in automobile manufacturing and in the aerospace, national defense, and electronic communication industries [1–4]. Mg-Al-RE alloy features high mechanical properties and creep resistance at room and high temperature [5,6]. Nonetheless, its strength at room temperature is unexceptional compared with traditional AZ91 (Mg–9Al–1Zn, wt.%) and A380 Al alloys, or the casting WE (Mg–Y-Nd) series [7,8].

There are several strengthening methods for casting magnesium alloys: grain boundary strengthening, solid solution strengthening [9] and second phase strengthening [10]. The combination of these strengthening methods is expected to obtain better mechanical properties. For magnesium alloys, the rapid cooling rate mainly controls grain refinement, and solid solution alloying is a more effective method to improve their mechanical properties. In order to maintain the high temperature resistance of Mg-4Al-RE-based alloys, a rare earth element (such as gadolinium, neodymium, or samarium) is selected as the alloying element. This can enhance the mechanical properties of magnesium alloys, because their atomic sizes are quite different from that of magnesium and feature great solubility in magnesium [11–15]. At high temperature, samarium features high solid solubility in magnesium and its atomic size is much larger than that of magnesium [16,17]. Therefore, forming a solid solution with samarium can improve the mechanical properties of magnesium alloys.

In recent years, more and more studies have reported improvements in the mechanical properties of magnesium alloys by adding samarium (Sm) [17–26]. Yang et al. [27] found...
that ASm44 alloy offered much higher elongation to fracture (ε) and a slightly higher tensile yield strength (TYS) than AE44 alloy, by approximately 193% and 6%, respectively, although the ultimate tensile strengths (UTS) were comparable. Nonetheless, the influence of Sm addition on microstructures and the mechanical properties of Mg-Al-RE-based alloys is still unclear. In this paper, samarium was used to modify Mg-4Al-4RE based alloy in order to further improve its mechanical properties.

In this work, the changes in microstructure and properties were studied by adding different contents of Sm into Mg-4Al-4 (La, Ce) alloy. Since the working environment of the Mg-4Al-4 (La, Ce) alloy was RT (room temperature) ~150 °C, the changes in the microstructure and properties of the alloy at 150 °C were closely analysed. The microstructure was analysed and characterized by scanning electron microscope (SEM, Zeiss-Supra 35VP, Carl Zeiss, Berlin, Germany) and transmission electron microscope (TEM, JEOL 2100F, Tokyo, Japan). Subsequently, the tensile mechanical properties of Mg-4Al-4 (La, Ce)-xSm alloy were tested at both room temperature (RT) and high temperatures. Finally, the influence of Sm addition on the microstructures, as well as the underlying strengthening mechanisms, were analysed and discussed.

2. Materials and Methods

The material used in the experiment was Mg-4Al-4 (La, Ce) alloy. The chemical composition of the alloy was determined by inductively coupled plasma atomic emission spectrometry (ICP-AES). The results are shown in Table 1. Commercial pure magnesium and pure aluminum were used for the alloy melting and Mn, La, Ce, and Sm elements were added in the form of Mg-5 wt.% Mn, Mg-25 wt.% La, Mg-25 wt.% Ce, and Mg-25 wt.% Sm master alloys.

Table 1. The actual chemical composition of the alloy was studied experimentally (wt.%).

| Alloys                  | Ce   | La   | Mn   | Al   | Sm   | Mg   |
|-------------------------|------|------|------|------|------|------|
| Mg-4Al-4 (La, Ce)       | 2.79 | 1.18 | 0.14 | 3.96 | 0    | Balance |
| Mg-4Al-4 (La, Ce)-1Sm   | 2.82 | 1.21 | 0.15 | 4.13 | 1.03 | Balance |
| Mg-4Al-4 (La, Ce)-2Sm   | 2.81 | 1.20 | 0.14 | 4.11 | 1.98 | Balance |

A cold-chamber die-casting machine was used for the die casting in the experiment. N2 + SF6 were used as the shielding gas in the melting process. The liquid metal was scooped into the die-casting machine by hand at 700 °C. The mold was equipped with an oil cooling and heating system and the oil heater temperature was set to 250 °C. During the high-temperature tensile test, when the temperature reached the predetermined temperature value, it was maintained for 30 min to ensure that the temperature of all parts of the sample was consistent. The dimension diagram of the tensile sample is shown in Figure 1. The dimension unit in the diagram was mm. The sample was cut from its middle part, and then the metallography was prepared. Firstly, the sample was finely ground on water-abrasive paper, then it was polished by a polishing machine and finally corroded with picric acid alcohol solution (29.4 g picric acid + 25 mL glacial acetic acid + 41 mL water + 350 mL alcohol).

After the sample was prepared, the microstructure of the alloy was observed by scanning electron microscope (SEM). The phase composition of the alloy was identified by X-ray diffraction (XRD) and energy dispersive spectrometer (EDS). For the XRD, continuous scanning mode was adopted; the 2θ range was from 10 to 80° and the scanning speed was 0.5°/min. The phase identification of the XRD used the International Centre for Diffraction Data (ICDD) database. During the preparation of the transmission electron microscope (TEM) samples, the samples were mechanically polished to about 50 µm, then a precision ion polishing system (PIPS 691, Gatan, Pleasanton, CA, USA) with a liquid nitrogen cooling system was used to polish the punched-out Φ 3 mm wafer thinning, and the excitation voltage and inclination angle were set to 4 kev and 4°, respectively. Using convergent beam electron diffraction (CBED) technology [28], the foil thickness of the given image was
determined, and the grain and phase sizes were calculated by digital micrograph software. In the tensile test, an Instron 3382 electronic tensile machine was used to test the mechanical tensile properties of the alloy. The test temperatures were RT, 150 °C, 200 °C, 250 °C, and 300 °C, and the strain rate was 0.5 mm/min. The presented values were the average of at least five measurements for each testing condition.

![Figure 1. Drawing of the tensile specimen dimensions.](image)

3. Results
3.1. Microstructures

Figure 2a,c,e show the microstructure and the secondary phase distribution in the Sm-free alloy and Sm-addition alloy. The grain size was measured by the cut-off point method. After adding Sm, the grain size did not change obviously. Although Al2Sm could be used as the heterogeneous nucleation point of Mg to refine the grain size [29], the refining effect was not obvious in this work. This might be because the alloy was prepared by die casting, the cooling rate could reach tens to hundreds of kelvin per seconds, and the grain size was mainly determined by the cooling rate. Figure 2b,d,f are four times larger than Figure 2a,c,e respectively. In Figure 2a,b, a large number of acicular eutectic phases in the grain boundary can be clearly observed. Figure 2c,d show that some acicular eutectic phases disappeared and granular phases precipitated. In Figure 2d,f, most of the acicular eutectic phases disappeared, α-Mg was surrounded by a small amount of eutectic phases, and a large number of block phases and a granular phase appeared in the grain and boundary. The addition of Sm reduced the fraction of the eutectic phase’s regions and induced the formation of other granular and block phases.

After the specimens of Mg-4Al-4 (La, Ce)-xSm alloy were stretched at different temperatures, in order to characterize the possible phase transformation during stretching at different temperatures, an XRD analysis was performed. Figure 3a,c presents the XRD pattern at RT, 150 °C, 200 °C, 250 °C, and 300 °C with different contents of Sm. The diffraction peaks from the intermetallic phases could be reasonably indexed by α-Mg, Al11RE3 and Al2RE, whereas a small part of the peaks could not be indexed by any known Al-RE or Mg-RE phases.

In order to further analyse the phase composition in the alloy from the perspective of micro-composition, the matrix phase and second phase in the Mg-4Al-4 (La, Ce) alloy with Sm were analysed by EDS. As shown in Figure 4, the Mg content at point 1 accounted for the vast majority, and the Al content was negligible; that is, point 1 was the matrix phase. From the corresponding EDS spectrum, along with the analysis results (Figure 5), the atomic ratio of Al:(La, Ce) was approximately 3:1. This further confirmed that the acicular phase was Al11RE3. From the corresponding EDS spectrum, along with the analysis results (Figure 6), the atomic ratio of Al:(La, Ce, Sm) was approximately 2:1. This further confirmed that the acicular phase was Al2RE. In Mg-4Al-4 (La, Ce)-15Sm alloy, the corresponding selected area electron diffraction (SAED) pattern (Figure 7b) confirmed that the acicular phase was Al11RE3, which featured approximately identical lattice parameters to Al11RE3; the corresponding SAED pattern (Figure 7d) confirmed that the granular phase was Al2RE, which featured approximately identical lattice parameters to Al2RE.

Figure 7a,c show a representative Bright-Field TEM (BF-TEM) image of the acicular phase in the Mg-4Al-4 (La, Ce)-1Sm alloy. The acicular phase was 0.2–4 µm long and
located particularly at the grain boundary. This phase is widely observed in the Mg-Al-RE system and most researchers believe it to be $\text{Al}_{11}\text{RE}_3$ (body-centered orthorhombic structure, $a = 0.443 \text{ nm}$, $b = 1.314 \text{ nm}$ and $c = 1.013 \text{ nm}$ [30]). The granular and block phases were $\text{Al}_2\text{RE}$ (face-centered cubic structure, $a = 0.8125 \text{ nm}$ [31]). The $\text{Al}_2\text{RE}$ phase and the $\alpha$-Mg matrix featured the following crystallographic orientation relationship:

\[
\begin{align*}
(111)_{\text{Al}_2\text{RE}} & / / (10\overline{1}1)_{\text{Mg}} \\
[01\overline{1}]_{\text{Al}_2\text{RE}} & / / (1210)_{\text{Mg}}
\end{align*}
\]

Figure 2. SEM images of the Mg-4Al-4 (La, Ce) alloy: (a,b) Mg-4Al-4 (La, Ce); (c,d) Mg-4Al-4 (La, Ce)-1Sm; (e,f) Mg-4Al-4 (La, Ce)-2Sm.
In order to further analyse the phase composition in the alloy from the perspective of micro-composition, the matrix phase and second phase in the Mg-4Al-4 (La, Ce) alloy with Sm were analysed by EDS. As shown in Figure 4, the Mg content at point 1 accounted for the vast majority, and the Al content was negligible; that is, point 1 was the matrix phase. From the corresponding EDS spectrum, along with the analysis results (Figure 5), the atomic ratio of Al:(La, Ce) was approximately 3:1. This further confirmed that the acicular phase was Al$_{11}$RE$_3$. From the corresponding EDS spectrum, along with the analysis results (Figure 6), the atomic ratio of Al:(La, Ce, Sm) was approximately 2:1. This further confirmed that the acicular phase was Al$_2$RE.

In Mg-4Al-4 (La, Ce)-1Sm alloy, the corresponding selected area electron diffraction (SAED) pattern (Figure 7b) confirmed that the acicular phase was Al$_{11}$RE$_3$, which featured approximately identical lattice parameters to Al$_{11}$RE$_3$; the corresponding SAED pattern (Figure 7d) confirmed that the granular phase was Al$_2$RE, which featured approximately identical lattice parameters to Al$_2$RE.

**Figure 3.** XRD patterns of Mg-4Al-4 (La, Ce) alloys with different Sm contents: (a) 0 wt.% Sm; (b) 1 wt.% Sm; (c) 2 wt.% Sm.

**Figure 4.** SEM image and the representative point EDS spectrum along with the analysis results of the matrix phase in the Mg-4Al-4 (La, Ce)-1Sm alloy.

**Figure 5.** SEM image and the representative point EDS spectrum along with the analysis results of the acicular eutectic phases in the Mg-4Al-4 (La, Ce)-1Sm alloy.
Figure 5. SEM image and the representative point EDS spectrum along with the analysis results of the acicular eutectic phases in the Mg-4Al-4 (La, Ce)-1Sm alloy.

Figure 6. SEM image and the representative point EDS spectrum along with the analysis results of the block phase in the Mg-4Al-4 (La, Ce)-1Sm alloy.

Figure 7. (a,c) BF-TEM image, (b,d) the corresponding SAED pattern with the analysis results of the acicular eutectic phases and block phases in the Mg-4Al-4 (La, Ce)-1Sm alloy.

3.2. Tensile Properties

Figure 8 shows the tensile curves of the Mg-4Al-4 (La, Ce) alloy with different Sm contents. The alloy exhibited obviously high YS and considerable strain hardening behaviour at RT. As the testing temperature increased, both YS and strain hardening gradually decreased. At least five specimen tests were performed at each temperature; the properties are shown in Figure 9 and the specific values are shown in Table 2. For comparison, the tensile properties of traditional Mg-Al-based alloys are also listed in Table 2 and Figure 9. At RT, the studied alloy exhibited even greater tensile properties than the newly devel-
oped Mg-4Al-4 (La, Ce) alloy, which was reported to feature the greatest strength-ductility balance in all Mg-Al-based alloys [32]. At high temperatures, the studied alloy features greater ductility than some Mg-Al-based alloys [5,32–38], albeit with comparable or slightly higher strength. Furthermore, although it features lower strength than Mg-4Al-4 (La, Ce) alloys [32], the Sm-addition alloy exhibited much higher ductility.

As shown in Figure 9 and Table 2, the ultimate tensile strength and elongation of the Sm-addition alloy decreased, but the yield strength increased at RT. With the increase in test temperature, the yield strength and ultimate tensile strength of the alloy generally decreased and the elongation increased first and then decreased. The yield strength of the 1–2%wt.% Sm-addition alloy at 150 °C was generally equivalent to that of the Sm-free magnesium alloys, while their elongation increased by 44.4% compared with the Sm-free alloys.

Figure 8. Representative tensile curve of Mg-4Al-4 (La, Ce) alloy after adding different contents of Sm (a) RT; (b) 150 °C; (c) 200 °C; (d) 250 °C; (e) 300 °C.
Figure 9. Mechanical properties of different alloys.

Table 2. Mechanical properties of Mg-4Al-4 (La, Ce)-xSm alloy and traditional Mg-Al-based alloy.

| Alloy                        | T (°C) | UTS (MPa)  | YS (MPa)  | ε (%) | Reference |
|------------------------------|--------|------------|-----------|-------|-----------|
| Mg-4Al-4 (La, Ce)            | RT     | 250.1 ± 2.5| 132.3 ± 1.3| 15.4 ± 3.4| This work |
|                              | 150    | 134.0 ± 0.7| 107.6 ± 0.8| 29.5 ± 2.3|           |
| Mg-4Al-4 (La, Ce)-1Sm        | RT     | 248.0 ± 2.4| 139.4 ± 5.4| 11.9 ± 1.4|           |
|                              | 150    | 129.9 ± 6.4| 108.0 ± 1.3| 42.6 ± 2.2|           |
| Mg-4Al-4 (La, Ce)-2Sm        | RT     | 242.0 ± 1.8| 135.5 ± 0.7| 10.9 ± 2.3|           |
|                              | 150    | 134.0 ± 0.7| 106.6 ± 0.1| 32.3 ± 4.2|           |
| AE44                         | 150    | 140        | 109       | 27    | [32]      |
| ALaSm432                     | 150    | 155 ± 5    | 120 ± 3   | 25 ± 4 | [33]      |
| AEX422                       | 150    | 199 ± 7    | 148 ± 3   | 9 ± 3  | [34]      |
| AX51                         | 150    | 161        | 102       | 7     | [4]       |
| AJ52                         | 150    | 164        | 108       | 14    | [4, 39]   |

The main factors affecting the tensile properties of Mg-4Al-4 (La, Ce) were [33, 34] the average grain size of the matrix, the solute solid solubility, the size, the quantity, and the morphology of the second phase. Firstly, the increase in yield strength could be analysed by through the Hall–Petch relationship, which showed that YS was directly proportional to D^{1/2} (D is the average grain size); the smaller the grain size, the higher the strength. The ultimate tensile strength and elongation decreased slightly and the yield strength increased slightly at room temperature, which might have been related to the decrease in the eutectic phase at the grain boundary because the decrease in the eutectic phase would increase the proportion of actual α-Mg. However, the yield strength was basically unchanged and the elongation of the alloy improved at 150 °C because the second-phase particles were embedded in the α-Mg matrix and the dislocation movement could be restrained, so the strength of the α-Mg matrix was improved. However, because Sm consumes part of the Al, the number of eutectic phases at the grain boundary was reduced and the grain boundary’s strengthening effect was reduced. The two mechanisms were superimposed on each other, resulting in a yield strength that was basically unchanged. However, due to the decrease in the eutectic structure, the proportion of α-Mg matrix increased, the number of dislocation initiations increased, and the elongation of the alloy was improved.
3.3. Fracture Analysis

Figures 10 and 11 show SEM micrographs of tensile fracture surfaces of Mg-4Al-4 (La, Ce) alloy with different Sm contents at RT and 150 °C respectively.

![SEM micrograph of fracture at room temperature](image1)

**Figure 10.** SEM micrograph of fracture at room temperature: (a) Mg-4Al-4 (La, Ce); (b) Mg-4Al-4 (La, Ce)-1Sm; (c) Mg-4Al-4 (La, Ce)-2Sm.

![SEM micrograph of fracture at 150 °C](image2)

**Figure 11.** SEM micrograph of fracture at 150 °C: (a) Mg-4Al-4 (La, Ce); (b) Mg-4Al-4 (La, Ce)-1Sm; (c) Mg-4Al-4 (La, Ce)-2Sm.

As can be seen from Figure 10, at room temperature, the dimple of the fracture surface of the Sm-free alloy was deeper and larger than that of the Sm-addition alloy, indicating that the alloy without Sm featured better ductility. It can be seen from Figure 11 that at 150 °C, the fracture surface of the Sm-free alloy featured a quasi-cleavage morphology, while the fracture surface of the Sm-addition alloy did not feature a cleavage morphology. It was composed of dimples of different sizes, and the dimples were deep. Its fracture mode was ductile. Compared with the 2 wt.% Sm-addition alloy, the dimples of the 1 wt.% Sm-addition alloy were smaller, which indicates that the alloy possessed better deformation ability; this was the reason for the better elongation of the 1 wt.% Sm-addition alloy.

4. Discussion

4.1. Multiple Dominant Intermetallic Phases

According to the relationship between the element interaction ability and the formation of the second phase, it is speculated that there should be Al₁₁RE₃ and Al₂RE phase in the alloy studied in this experiment. Previous studies showed that [40,41] in die-casting AE42 alloy containing cerium-rich mixed rare earth, with the addition of other rare earth elements, more polygonal Al₂RE phases appeared at the eutectic phase composed of Al₁₁RE₃ phase and Mg at the grain boundary, which meant that the Al₁₁RE₃ in cerium-rich mixed rare-earth magnesium alloy was unstable and partially decomposed into Al₂RE and Al. Lv et al. [42] calculated the entropy of Al₁₁RE₃ and Al₂RE, and the results showed that except for RE = Pm, Lu and Sc, the entropy of most of the Al₂RE phases was greater than that of the Al₁₁RE₃ phase, and that Al₁₁RE₃ phase in cerium-rich mixed rare-earth magnesium alloy was easy to decompose into Al₂RE and Al at higher temperatures [4,32,40]. Liao et al. [43] studied the solidification and precipitation behaviour of AE42 magnesium alloy and found that two rare earth compounds precipitated during solidification: one was massive Al₂RE phase, which was formed near 616 °C; the other was Al₁₁RE₃ phase, which precipitated at 604 °C. The solidification structure of the AE42 alloy was composed of α-Mg matrix, Al₁₁RE₃ phase, and Al₂RE phase, and the solidification path of the alloy was liquid→α-Mg→α-Mg + Al₂RE→α-Mg + Al₂RE + Al₁₁RE₃. Jia et al. [44] studied the
liquid projection diagram of Mg-Al-Sm alloy and found that after adding Sm to Mg-4Al-4 (La, Ce) alloy, Al$_2$RE phase was formed near 720 °C and precipitated preferentially to Al$_{11}$RE$_3$ phase.

Because Sm, La, and Ce belong to a group of light rare earths, they feature similar chemical properties. La and Ce atoms easily accumulate around Sm atoms, thus promoting the growth of Al$_2$RE phase. At the same time, some Al, La, and Ce atoms will be consumed, reducing the overall number of Al$_{11}$RE$_3$ phases formed in the alloy. In this work, with the increase in Sm element addition, the solidification path of the alloy was: liquid$\rightarrow$α-Mg$\rightarrow$α-Mg + Al$_2$RE$\rightarrow$α-Mg + Al$_2$RE + Al$_{11}$RE.

4.2. Mechanical Property Analysis

The mechanical properties of the Mg-4Al-4 (La, Ce)-1Sm alloy showed very good plasticity, and its yield strength was basically equivalent to the Sm-free alloy at 150 °C. It is considered that the effect of Sm on the properties of Mg-4Al-4 (La, Ce) alloy was the result of the comprehensive combination of the following aspects.

Because there are many factors affecting the properties of the alloy at high temperature, the strength of the alloy at RT is calculated first. The strength of Mg-4Al-4 (La, Ce) alloy with Sm was mainly the result of the interaction of solute atoms, grain boundaries, and second phase strengthen. Accordingly, the yield strength ($\sigma_s$) can be expressed as:

$$\sigma_s = \sigma_{ss} + \sigma_{gb} + \sigma_p$$

where $\sigma_{0}$, $\sigma_{gb}$, and $\sigma_p$ are the strength contributed by the solution strengthening, grain boundary strengthening, and second phase strengthening, respectively.

(1) Solid solution strengthening

Jia et al. proposed a solid solution strengthening model similar to Labusch and Fleischer’s strength-related model ($\sigma_{ss}$), which is evaluated by the following formula [45]:

$$\sigma_{ss} = \sum k_i c_i^{2/3}, \ (i = \text{Al})$$

where $k$ is the constant and $c$ is the solid solubility of the solute atoms. With the increase in Al content, the solid solution $c$ gradually increased, so the yield strength of the alloy gradually increased with the increase in Al content. Combined with previous research [46], $k_{Al} \approx 197.5$ MPa (at.%)$^{2/3}$, according to the previous analysis, as shown in Figure 4, the solid solution of Al atom is 0.74%.

Han et al. [47,48] systematically studied the solid solution strengthening effect of rare earth elements on magnesium alloys and calculated the solid solution strengthening coefficient K of the solute elements. Jiang et al. [49] used a similar strength model to calculate the strength of the alloy at room temperature, which was similar to the experimental data.

(2) Grain boundary strengthening

According to the statistics of the grain size, when 1 wt.% Sm is added, the grain size decreases slightly, about 0.15 μm. However, the grain size becomes larger in the alloy with 2 wt.% Sm. According to the Hall–Petch formula [50]:

$$\sigma_{gb} = \sigma_0 + k_{HP}d^{-1/2}$$

where $\sigma$ is the yield strength of the alloy; $\sigma_0$ is the lattice resistance of the dislocation movement (usually related to the type and quantity of alloying elements dissolved into the matrix and the type, quantity, and shape of precipitation-strengthened second phase), which can be equivalent to the yield strength of Mg solid solution in this system. The value $d$ is the average grain diameter; $k$ is the fine grain strengthening coefficient; and the range of $k$ value is generally 170 MPa (μm)$^{1/2}$−400 MPa (μm)$^{1/2}$, which depends on the density and stability of the upper dislocation source at the grain boundary, and is also affected by
the segregation of solute atoms at the grain boundary [51]. In this experiment, the $d$ values are 4.98 μm, 4.83 μm and 4.88 μm respectively.

(3) Second phase strengthening

The primary second phase was not found in this experiment, but there was a certain precipitation of the second phase; it was difficult to create statistics because of the randomness of their positions, and there is no available theoretical formula for the strength prediction of second-phase strengthening. However, in general, it will increase dislocation stacking and improve properties.

For the Sm-free alloy, because there was no second phase particle formation, its yield strength was 132 MPa. Using the solid solution strengthening and grain boundary strengthening model, the $k_{HP}$ value is calculated as 253 MPa (μm)$^{1/2}$.

The known values are brought into Equations (2) and (3) to calculate the strength of the Sm-addition alloy, for alloys containing 1 wt.% and 2 wt.% Sm, the values of strength are 133.6 MPa and 133.5 MPa, which are slightly lower than the experimental values. After the Sm-addition alloys, Sm reacts with Al before Ce and La to form Al$_2$RE phases. Al$_2$RE acts as a dislocation pinning in the α-Mg matrix. The deviation may be caused by the emergence of the second phase.

Through the above analysis, under the condition of adding Sm to alloy Mg-4Al-4 (La, Ce), the Al$_{11}$RE$_3$ is reduced, the grain size is refined a little, and Al$_2$RE strengthening phase is produced in the grain and boundary, which leads to basically unchanged yield strength and greatly improved elongation.

The above is the room temperature strength analysis of Mg-4Al-4 (La, Ce)-xSm alloy. Under high-temperature conditions, due to the lack of high temperature data, quantitative calculation was no longer carried out; only qualitative analysis was carried out. At high temperature, the second phase particles feature high temperature stability and can play the role of pinning dislocations, so they possess a certain high temperature strengthening ability. Although the addition of Sm reduces grain boundary strengthening, second-phase strengthening is introduced. Under the combined action of the two strengthening mechanisms conditions, the high temperature yield strength does not decrease.

5. Conclusions

The microstructure, tensile properties, and strengthening mechanism of Mg-4Al-4 (La, Ce) alloy with Sm were studied. The results show that:

(1) The addition of samarium to Mg-4Al-4 (La, Ce) alloy reduces the precipitation of Al$_{11}$RE$_3$ and weakens grain boundary strengthening, but also introduces the second phase of Al$_2$RE. Al$_2$RE can play the role of pinning dislocations and strengthen the α-Mg matrix, especially at high temperatures; it features good high-temperature stability, which is the main reason why the high temperature yield strength of the alloy does not decrease.

(2) After adding Sm, the ultimate tensile strength and elongation of Sm-addition alloy decrease, but the yield strength increases at RT. The yield strength, ultimate tensile strength, and elongation of the alloy are 108.0 MPa, 129.9 Mpa, and 42.6%, respectively, at 150 °C. This suggests very good plasticity.

(3) Based on the analysis of the effect of the addition of Sm on the high-temperature properties, the second-phase particles feature high temperature stability and can play the role of pinning dislocations, so they have a certain high-temperature strengthening ability. Although the addition of Sm reduces grain boundary strengthening, second-phase strengthening is introduced. Under the combined action of the two strengthening mechanisms conditions, the high-temperature yield strength does not decrease.
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