Synergistic effects of Y and Nd on grain refinement of Mg-Y-Nd-Al alloy

Lili Zhao\(^1\), Liping Wang\(^1\), Lei Wang\(^1\), Yicheng Feng\(^1\), Rui Fan\(^1\), Sicong Zhao\(^1\) and Yuanke Fu\(^1\)

\(^1\) School of Material Science and Chemical Engineering, Harbin University of Science and Technology, Harbin, 150040, People’s Republic of China
\(^2\) College of Light Industry, Harbin University of Commerce, Harbin, 150028, Heilongjiang, People’s Republic of China

E-mail: wangxiaolei2005@126.com

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Abstract

In this study, the synergistic effects of Y and Nd on the grain refinement of the as-cast Mg-Y-Nd-Al alloy was investigated by varying Y and Nd contents while fixing their total content (Y + Nd) at 7%. When the contents of Y and Nd were 3% and 4%, respectively, the refinement was most effective and the smallest grain size of 49 ± 5 μm was achieved. The grain refinement process was primarily controlled by the heterogeneous nucleation and the growth restriction factor (Q value). Y could only form Al\(_2\)RE phase with Al, while both Al\(_2\)RE and Al\(_{11}\)RE\(_3\) were formed between Nd and Al. The Al\(_2\)RE phase acted as nucleation particles of α-Mg and facilitated heterogeneous nucleation; however, Al\(_{11}\)RE\(_3\) was an unfavorable phase for heterogeneous nucleation. When the Y content was less than 3%, the quantity of Al\(_2\)RE phase increased when more Y was available, which resulted in more active nucleation particles and better refinement. When the Y content exceeded 3%, the Q value (growth limiting factor) of the alloy decreased, while the quantity of Al\(_2\)RE phase remained unchanged. This would lead to a decreased number of active nucleation particles and a less effective grain refinement.

1. Introduction

Magnesium alloys show great potentials in the lightweight automobile and aerospace industries [1, 2] because of their low density, good casting performance, easy processing and recycling; however, this application is seriously limited by their low strength and poor plasticity [3]. Fine aging precipitates can be introduced to Mg alloys by adding rare-earth (RE) elements such as Nd, Sm, Y, and Gd [4]. In recent years, the development of high-performance Mg-RE alloys has gained increasing research attention [5–7]. Mg alloys with fine grains generally have higher strength, hardness, plasticity and toughness than those with coarse grains, especially for Mg alloys with less room-temperature slip systems [8]. However, binary or ternary Mg-RE alloys usually possess a coarse grain size, which impedes the effectiveness of precipitation strengthening of the alloy. Therefore, grain refinement is required for the practical application of Mg-RE alloys. Zr is the most common grain refiner [9] because of the solute effect of the dissolved Zr and the heterogeneous nucleation of the undissolved Zr [10]. However, some disadvantages of Zr refinement, such as the difficulty in preparing Mg-Zr master alloys, high cost, and easy deposition of Zr particles [11, 12], warrant the need to develop new types of refiner. Previous investigations show that Al [13], Mn [14], and ZrB\(_2\) [15] can all refine the grain size of Mg-RE alloy. Among them, Al is the most promising candidate due to its low cost and strong refinement effect. Thus extensive efforts have been invested to study the Al refinement of Mg-RE alloys [13, 16–19].

The mechanism of Al refinement is that Al reacts with RE to form Al\(_2\)RE particles in situ which can lower its interfacial energy with α-Mg and act as heterogeneous nucleation particles to refine the alloy [20]. Owing to the variations in RE elements and the types of Mg-RE alloys, diverse second phases could be developed during the Al refinement. They are varied in composition, content, and distribution, which are closely related to the effectiveness of refinement. For example, in the Mg-Nd alloys refined by Al, the acicular Al\(_{11}\)Nd\(_3\) phase was preferentially formed with an increase in Al content. The best refinement effect was achieved when the Al...
content was greater than 2% and the Al2Nd phase started to emerge [18]. In the Mg-Y alloys refined by Al where only the Al2Y phase was formed; less than 1%Al content could result in the best refinement [13]. The Mg-RE alloys used in industries are usually multi-component RE alloys, and the type and content of RE will inevitably affect the effectiveness of the refinement. Liu et al. [21] reported that the Gd and Y contents in Mg-Gd-Y-Al alloys had significant impact on the phase composition and the refinement outcomes; nevertheless, the refinement mechanism has not been revealed.

Mg-Y-Nd-Zr (WE series) alloys are currently the most widely used commercial Mg-RE alloys. Based on the WE series, Zr was replaced with Al to develop a low-cost Mg-Y-Nd-Al alloy [22]. Within this study, by fixing the total content of RE and Al in the alloy and varying the ratio between Y and Nd, the effects of Y and Nd contents on the grain refinement of Mg-xY-(7-x)Nd-2Al (x = 0, 1, 2, 3, 4, 5, 6, 7) alloys were studied.

2. Experimental methods

The experimental Mg-Y-Nd-Al alloy ingots were prepared by the raw materials concluded pure Mg, pure Al, Mg-30Nd, and Mg-30Y master alloys. The Mg-Y-Nd-Al alloys were melted in the steel crucible heated by a resistance furnace; the mass of the melt was 1 kg. During melting, 99.5 vol% SF6 and 0.5 vol% CO2 mixed gases were used to prevent from oxidation of Mg. First, pure Mg was melted at 720 °C, then Mg-30Nd and Mg-30Y master alloys were added, and finally pure Al was added. After the raw materials were completely melted, the melt was manually stirred for 2 min and then kept at 750 °C for 30 min, and then the melt was poured into a permanent mold coated with ZnO (cavity size: 100 × 10 × 60) preheated at 200 °C for 2 h to ensure the fluidity of the melt. The sketch of the ingot is shown in figure 1. The nominal and tested compositions of Mg-xY-(7-x)

![Figure 1. The sketch of the ingot.](image-url)
Nd-2Al\((x = 0, 1, 2, 3, 4, 5, 6, 7)\) alloys prepared in the present paper are shown in Table 1, which were determined by inductively coupled plasma optical emission spectrometer (ICP-6300).

The sampling position of the research is shown in Figure 1. The microstructure of as cast Mg-Y-Nd-Al alloy was observed by optical microscope OM (XD30M) in polarized mode, and the grain size was measured by linear intercept method. The micro-structural observing samples were obtained by a standard preparation of metal graphic specimens. After polishing, the metallographic sample was etched with corrosive agent (picric acid 10g, glacial acetic acid 15 ml, distilled water 20 ml, ethanol 120 ml). The phase composition of the alloy was characterized by x-ray diffraction (XRD)(X’PertPRO) with scanning angle of 10° ~ 90°, and scanning speed of 2° min\(^{-1}\). The microstructure of the alloy was further observed by scanning electron microscope(SEM) (APREOC), and the composition of intermetallic phases in the alloy was analyzed by energy dispersive spectrometer (EDS). The volume fraction of the intermetallic phase in the alloy and the number density of the possible effective nucleating particles inside the grains were calculated by using point recording method.

Figure 2. The optical microstructure of the alloy under the as-cast Mg-\(x\)Y-(7-\(x\))Nd-2Al\((x = 0, 1, 2, 3, 4, 5, 6, 7)\): (a) EA72; (b) WEA162; (c) WEA252; (d) WEA342; (e) WEA432; (f) WEA522; (g) WEA612; (h) WA72.
3. Experimental and testing results

3.1. Grain size

Figures 2 and 3 present the optical microstructure and grain size of the as-cast Mg-Y-Nd-Al alloy, respectively. As shown in figure 2(a), coarse dendrites are observed in the EA72 alloy which do not have any Y content, and its average grain size is $184 \pm 18 \mu m$. Comparatively, equiaxed grains are distinct when Y is introduced. With the increase in Y content, the grain size decreased gradually. The smallest grain size ($49 \pm 5 \mu m$) is obtained when the Y content is 3% in the WEA432 alloy. With the further increase in Y, the grain size slightly (figures 2(b)–(h)).

Figure 3. The grain size of the alloy varies under the as-cast Mg-xY-(7-x)Nd-2Al (x = 0, 1, 2, 3, 4, 5, 6, 7) alloys.

Figure 4. XRD pattern of as-cast Mg-xY-(7-x)Nd-2Al (x = 0, 1, 2, 3, 4, 5, 6, 7) alloys.
It was reported that under the same temperature gradient, the microstructure of the alloy is closely related to heterogeneous nucleation [23]. More heterogeneous nucleation occurs in the melt, stronger grain separation and more free grains are expected. Our results indicate that the addition of Y promotes heterogeneous nucleation in the alloy, leading to inhibited grain growth and the formation of equiaxed grains.

3.2. Phase analysis

Figure 4 shows the x-ray diffraction pattern of the as-cast Mg-Y-Nd-Al alloy, where $\alpha$-Mg matrix, Al-RE intermetallic phase ($\text{Al}_2\text{RE}, \text{Al}_{11}\text{RE}_3$), and Mg-RE intermetallic phases ($\text{Mg}_{12}\text{RE}, \text{Mg}_{24}\text{RE}_5, \beta_1$-$\text{Mg}_{14}\text{Nd}_2\text{Y}$) can be identified. Table 2 summarizes the phase composition of the alloys, which is strongly dependent on the contents of Y and Nd. When the Y content is less than or equal to 3%, the Al-RE intermetallic phase is mainly $\text{Al}_2\text{RE}$ and $\text{Al}_{11}\text{RE}_3$; when the Y content exceeds 3%, the intermetallic phase of Al-RE is dominated by $\text{Al}_2\text{RE}$. In addition, with the increase in Y content, the Mg-RE intermetallic phase gradually changes from $\text{Mg}_{12}\text{RE}$ to $\beta_1$, and then to $\text{Mg}_{24}\text{RE}_5$.

An intermetallic compound in the alloys was determined by its enthalpy of formation. When the compound has a more negative enthalpy of formation, it is easier to be formed. The Miedema semi-empirical model (equations (1) and (2)) is usually used to calculate the enthalpy of formation [24]:

$$
\Delta H_{AB} = f_B \times \frac{x_A[1+\mu_A x_B(\Phi_A-\Phi_B)]}{x_A V_A^{2/3} [1+\mu_A x_B(\Phi_A-\Phi_B)] + x_B V_B^{2/3} [1+\mu_B x_A(\Phi_B-\Phi_A)]}
$$

$$
f_{AB} = 2p V_A^{2/3} V_B^{2/3} \times \frac{2\left[(n_{ws})^{1/3}_A -(n_{ws})^{1/3}_B\right]^2-(\Phi_A-\Phi_B)^2 - a^2}{(n_{ws})^{1/3}_A + (n_{ws})^{1/3}_B}
$$

where $x_A$ and $x_B$ are the mole fractions of A and B, respectively, $V$ is the molar volume, $n_{ws}$ is the electron density, $\Phi$ is the electronegativity/negativity, and $p$, $q$, $r$, $a$, and $\mu$ are empirical parameters. The physical and empirical parameters were selected according to references [25] and [26]. Figure 5 shows the calculated enthalpy of formation for each phase. Al-RE phases ($\text{Al}$-$\text{Nd}$ and $\text{Al}$-$\text{Y}$ phases) have more negative enthalpy of formation than Mg-RE, Mg-Y and Mg-Al phases, implying that they are more favorable intermetallic compounds in Mg-Nd-Y-Al quaternary alloy. When all Al is consumed, RE elements ($\text{Nd}$ and $\text{Y}$) can react with Mg to form the Mg-RE phases.

3.3. Microstructure

SEM images of the as-cast Mg-Y-Nd-Al alloys are shown in figure 6. Three types of second phases were identified in all alloys, i.e., polygonal (“A” in figure 6), acicular (“B” in figure 6) and eutectic second phase (“C” in figure 6). The EDS analysis results of “A”, “B”, and “C” phases in each alloy are presented in tables 3–5, respectively.

The polygonal second phase is mainly found inside the grain. It has the same morphology in different alloys, and its size ranges between 2 $\mu$m and 12 $\mu$m. As shown in table 3 that these polygonal phases primarily contain Al and RE (Nd, Y) elements, and the atomic ratio between Al to RE is close to 2:1. The acicular phase is largely located near the grain boundaries, and its morphology significantly depends on the composition of the alloy. In EA72, WEA162, and WEA252 alloys with less than 3% Y content, more acicular phases are observed with...
smaller grain size and smaller spacing between the phases. When the Y content is more than 3%, the quantity of acicular phase decreases while its size increases. For example, in WEA612 and WA72 alloys with higher Y content, a small quantity of a thicker acicular phase is observed near the grain boundary, as shown in figures 6(g), and (h)). Table 4 suggests that Al11RE3 is the main acicular phase when the Y content is "3%, and it transforms into the Al2RE when the Y content is higher than 3%. The eutectic phase is located at the triangular grain boundary, and its morphology is very similar to that of eutectic phase found in the Mg-Y-Nd alloy without adding Al. As shown in table 5, the elements detected in the eutectic phase are Mg, Nd and Y, which is consistent with the XRD results suggesting the eutectic phases of Mg-Y-Nd alloy are mainly Mg12Ndβ1-Mg14Y2Ndβ1-Mg24Y5β1.

Figure 7 shows the volume fraction of the intermetallic phase in the as-cast Mg-Y-Nd-Al alloys. When the Y content increases, the formation of a polygonal phase and an acicular phase is promoted and inhibited, respectively. The volume fraction of the eutectic phase also depends on the Y content. WEA342 alloy has the most eutectic phase (volume fraction is 3.8%) while almost no eutectic phase is found in the WA72 alloy. It indicates that a high Y content is not favorable for the formation of the eutectic phase. According to the Al-Mg-Nd ternary phase diagram [30] and the study of Liu et al [21], the polygonal Al12Nd phase may precipitate directly from the melt prior to the precipitation of the α-Mg phase. With a decrease in temperature, the acicular Al14Nd3 phase can be formed through a eutectic reaction and emerge along the dendrite boundary with distinct eutectic characteristics. In the EA72 alloy, the quantity of polygonal Al12Nd
phase was very small, suggesting a minor Al consumption in this stage. Therefore, in the eutectic reaction, high Al availability facilitates the formation of needle-like $\text{Al}_{11}\text{Nd}_3$ phases. The Mg-Y-Al alloy experienced a similar solidification process with the formation of different Al-RE phases. Chang et al.\[31\] showed that in Mg-Y-Al alloys, the Al-RE phase are $\text{Al}_2\text{Y}$ formed prior to $\alpha$-Mg precipitation and eutectic precipitation. When Y/Al is greater than 1.5, the polygonal $\text{Al}_2\text{Y}$ phase is formed mainly prior to $\alpha$-Mg precipitation. In this study, the Y/Al ratio of the WA72 alloy is 3.5, the formation of polygonal $\text{Al}_2\text{Y}$ phase is favorable. Therefore, with the increase in Y content, the quantity of polygonal $\text{Al}_2\text{RE}$ phases increases with more consumption of Al, subsequently less acicular Al-RE phases are produced in the eutectic reaction.

Within this study, RE is abundant in all the alloys wherein the Mg-RE eutectic phase is formed under the condition of non-equilibrium solidification. The solid solubility of Y and Nd in the Mg matrix determines the eutectic phase content, i.e., Y with a higher solid solubility, is more likely to develop a solid solution in the Mg matrix, while Nd with a lower solid solubility is preferably to form a eutectic structure. When the Y content is small, it partially replaces Nd in the intermetallic phase of Al-RE (tables 3 and 4), resulting in a surplus of Nd and the formation of the Mg-RE eutectic phase. With the increase in Y content, more Nd in the alloy is replaced by Y and the remaining Y element increases, resulting in more eutectic phases. Therefore, with the increase in Y content, the quantity of eutectic phases increases slightly at first, and then decreased significantly.

**Table 3. EDS analysis of polygonal phase.**

| Locations | Alloys | Mg   | Nd | Y   | Al   | Results       |
|-----------|--------|------|----|-----|------|---------------|
| A         | EA72   | 4.03 | 35.32 | —   | 60.65 | $\text{Al}_2\text{Nd}$ |
|           | WEA162 | 4.48 | 22.83 | 10.95 | 61.74 | $\text{Al}_2\text{RE}$ |
|           | WEA252 | 8.31 | 17.12 | 14.32 | 60.25 | $\text{Al}_2\text{RE}$ |
|           | WEA342 | 5.34 | 9.04  | 24.83 | 60.79 | $\text{Al}_2\text{RE}$ |
|           | WEA432 | 7.61 | 6.08  | 26.06 | 60.23 | $\text{Al}_2\text{RE}$ |
|           | WEA522 | 6.77 | 3.64  | 30.39 | 59.2  | $\text{Al}_2\text{RE}$ |
|           | WEA612 | 9.43 | 1.66  | 31.11 | 57.8  | $\text{Al}_2\text{RE}$ |
|           | WA72   | 7.42 | —     | 33.26 | 59.33 | $\text{Al}_2\text{Y}$ |

**Table 4. EDS analysis of acicular phase.**

| Locations | Alloys | Mg   | Nd   | Y   | Al   | Results       |
|-----------|--------|------|------|-----|------|---------------|
| B         | EA72   | 72.4 | 6.04 | —   | 21.56 | $\text{Al}_{11}\text{Nd}_3$ |
|           | WEA162 | 81.93| 3.35 | 0.8 | 13.92 | $\text{Al}_{11}\text{RE}_3$ |
|           | WEA252 | 86.05| 1.94 | 1.59| 10.42 | $\text{Al}_{11}\text{RE}_3$ |
|           | WEA342 | 83.52| 1.47 | 3.15| 11.86 | $\text{Al}_{11}\text{RE}_3$ |
|           | WEA432 | 66.74| 2.03 | 8.31| 22.92 | $\text{Al}_2\text{RE}$ |
|           | WEA522 | 75.45| 0.91 | 7.2 | 16.44 | $\text{Al}_2\text{RE}$ |
|           | WEA612 | 67.75| 0.49 | 10.01| 21.75 | $\text{Al}_2\text{RE}$ |
|           | WA72   | 88.4 | —    | 3.5 | 7.1   | $\text{Al}_2\text{Y}$ |

**Table 5. EDS analysis of eutectic phase.**

| Locations | Alloys | Mg   | Nd   | Y   | Al   | Results       |
|-----------|--------|------|------|-----|------|---------------|
| C         | EA72   | 92.61| 6.25 | —   | 1.14 | $\text{Mg}_{12}\text{Nd}$ |
|           | WEA162 | 92.55| 6.53 | 0.11| 0.81 | $\text{Mg}_{12}\text{RE}/\beta_1$ |
|           | WEA252 | 91.99| 6.47 | 0.51| 1.03 | $\text{Mg}_{12}\text{RE}/\beta_1$ |
|           | WEA342 | 92.73| 5.67 | 0.82| 0.78 | $\text{Mg}_{12}\text{RE}/\beta_1$ |
|           | WEA432 | 94.01| 3.83 | 1.54| 0.62 | $\text{Mg}_{24}\text{RE}_5/\beta_1$ |
|           | WEA522 | 91.25| 4.48 | 3.21| 1.06 | $\text{Mg}_{24}\text{RE}_5/\beta_1$ |
|           | WEA612 | 92.16| 2.74 | 4.33| 0.77 | $\text{Mg}_{24}\text{RE}_5$ |
|           | WA72   | 70.31| —    | 29.26| 0.39 | $\text{Mg}_{24}\text{Y}_5$ |
3.4. Heterogeneous nucleation particle

It was reported that there is an orientation relationship between the Al2RE phase (RE = Y, Gd, Nd, Ce, or Sm) and the α-Mg matrix in Mg-RE-Al alloy [21], i.e., [101]Al2RE || [1110]Mg, (222)Al2RE || (0002)Mg. Under this set of orientation, the misfit between Al2RE and α-Mg is less than 2%, which is a complete wetting. Thus Al2RE can act as heterogeneous nucleation particles for α-Mg. For the alloys herein, a polygonal Al2RE phase containing Y and Nd are observed inside the grains (table 3). Figure 8 shows the TEM morphology and HRTEM images of the particle phase in alloy when the Y content is 3%. Through the diffraction spots obtained by Fourier transformation, it shows that the Al2RE phase has a face-centered cubic (fcc) structure with a d spacing of (111) approximately 0.46 nm and a lattice constant approximately 0.79 nm. This lattice constant is between Al2Nd phase (fcc, a = 0.80 nm) and Al2Y phase (fcc, a = 0.76 nm), and the misfit between α-Mg and Al2RE containing Y and Nd elements is less than 2%. It is confirmed in the present study that Al2RE phases located inside the grain can act as nucleation particles and play an important role in the grain refinement of the alloy.

In general, the number of effective nucleation particles (located inside the grains) is the main factor determining the grain size of the alloy. A higher number of effective nucleation particles are associated with a smaller final grain size [19–21]. Figure 9 shows the statistics on the number density of effective nucleation particles in the Mg-Y-Nd-Al alloys. In the EA72 alloy, the number density of effective nucleation particles is 58 ± 32 pcs mm⁻², which corresponds to the coarse grain size of the alloy. With the increase in Y content, the number density of the effective nucleation particles increases gradually and reaches a maximum of 305 ± 16 pcs/mm² in the WEA342 alloy when the grain size of the alloy is the smallest. With the further increase in the Y content, the number of effective nucleation particles decreases moderately, leading to a slightly smaller grain size.
4. Discussion and analysis

Our results demonstrate that a higher Y content in the Mg-Y-Nd-Al alloy facilitates the formation of the Al₂RE phase and increases the number of heterogeneous nucleation particles, which is beneficial for grain refinement. When the Y content is higher than 3%, the quantity of the Al₂RE phase remains unchanged; however, the number of effective Al₂RE nucleation particles decreases, resulting in grain coarsening. This indicates that the occurrence of nucleation is affected by the solute.

Previous studies on grain refinement of Al, Mg, and Ti cast alloys [32–34] have suggested that the interaction between the solute and nucleation particles contributed significantly to the grain refinement of the cast metals. The free growth theory [35] stipulated that the undercooling required for nucleation (ΔT_n) is inversely proportional to the size of the nucleating sites and nucleation always occurs preferentially on large particles. The size of the Al₂RE nucleation particles in the Mg-Y-Nd-Al alloy ranges from 1 to 12 μm. At a certain cooling rate, the number of Al₂RE particles that can be activated to become effective nucleation particles depends on the undercooling provided by the solution. When the undercooling of a component formed by the solute (ΔT_s) [33] is greater than ΔT_n, heterogeneous nucleation is excited. The expansion rate of the undercooling zone of the solute can be measured by the growth restriction factor (Q value) [36, 37]. A high Q value is associated with a fast construction of the supercooled zone, leading to the activation of more nucleation particles. In this case, further growth of the grains is restrained and an effective grain refinement is achieved. Figure 10 is a schematic based on interdependence theory, which is commonly used to explain the relationship between the solute and

![Figure 9](image9.png) **Figure 9.** The number density of Al₂RE particles in the alloy under the as-cast Mg-xY-(7-x)Nd-2Al(x = 0, 1, 2, 3, 4, 5, 6, 7).

![Figure 10](image10.png) **Figure 10.** Schematic diagram of the effect of solute and component super cooling on nucleation: (a) Alloys with low Q value; (b) Alloys with high Q value, where θ is the equilibrium liquidus temperature, T_A is the actual temperature and dgs is grain size.
nucleation [38]. A high Q value corresponds to a large composition undercooling of the components, which further stimulates small Al$_2$RE particles that may be difficult to be activated when a low Q value is present.

In a multivariate system, the Q value is defined as $Q = \sum m_i C_i (k_i - 1)$, where, $m$ is the liquidus slope, $C$ is the solute concentration, $k$ is the equilibrium distribution coefficient, and $i$ represents different solutes [24]. The corresponding parameters of the Y, Nd, and Al elements are presented in table 6 [25]. The Q values of the Mg-Y-Nd-Al alloys are shown in table 7. It can be observed that the Q value of the alloy decreases with increasing Y content. When the Y content is less than 3%, the quantity of Al$_2$RE phase would increase with the increase of Y content. Despite of a decreasing Q value of the alloy, the speed of constructing a supercooled zone maintained at a high level. In this case, more Al$_2$RE particles can act as heterogeneous nucleation sites, and the microstructure of the alloy is refined. When the Y content was higher than 3%, the quantity of the Al$_2$RE phase remain unchanged; however, the Q value of the alloy further decreased with an increase in Y content. Some of the small Al$_2$RE particles cannot be activated because the construction speed of the supercooled zone slowed down, resulting in a decrease in the number of effective Al$_2$RE nucleation particles and an increase in grain size.

5. Conclusion

(1) In the Mg-Y-Nd-Al alloy, by fixing the total content of RE (Y and Nd) at 7%, the synergistic effects of varying Y and Nd contents on the grain refinement were studied. With the increase in Y content, the grain size of the alloy decreases at first and then increases. When the Y and Nd contents were 3% and 4%, respectively, the most effective refinement was achieved with a smallest grain size of 49 ± 5 μm.

(2) The grain refinement process is mainly controlled by the heterogeneous nucleation and the growth restriction factor (Q value). The Al$_2$RE phase can act as nucleation particles for α-Mg and play an important role in refining the grain. When the Y content was < 3%, the quantity of Al$_2$RE phase increased when more Y is available. Despite of a decreasing Q value of the alloy, more Al$_2$RE particles can be activated as nucleation particles, and the microstructure of the alloy is refined. When the Y content exceeds 3%, the quantity of the Al$_2$RE phase remain unchanged; however, the Q value of the alloy further decreased. Some of the small Al$_2$RE particles cannot be activated, resulting in a decrease in the number of nucleation particles and a less effective grain refinement.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.
ORCID iDs
Liping Wang https://orcid.org/0000-0002-6856-7527
Lei Wang https://orcid.org/0000-0003-1310-8603
Sicong Zhao https://orcid.org/0000-0003-0689-399X

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