Materials Research Express

PAPER

Effect of La/Nd ratio on microstructure and mechanical properties of as-cast AZ91-xLa/Nd alloy

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Keywords: AZ91, rare earth, microstructure, mechanical properties, growth mechanism

Abstract

The effect of La/Nd ratio on microstructure and mechanical properties of as-cast AZ91D alloys were investigated. The alloys were produced by casting the molten metal into a preheated steel mould. Microstructures were investigated by XRD and SEM (equipped with EDS). The hardness measurement was carried out by Brinell hardness (HB) digital display tester. Compression tests were conducted at both room and high temperatures (20 °C and 150 °C). Microstructural characterizations reveal that the area fraction of the $\beta$-Mg$_{17}$Al$_{12}$ phase changed with the variation of La/Nd ratio. The area fraction of the $\beta$-Mg$_{17}$Al$_{12}$ phase decrease significantly and then increased slightly with the increase of La/Nd ratio. Besides, the results show that the addition of La and Nd contributed to the formation of needle-like phase Al$_{11}$RE$_3$. Meanwhile, the Brinell hardness and high-temperature compression properties of this alloy reach the maximum values (67 HB and 330 MPa, respectively) when the La/Nd ratio is 2/3. In this alloy, the amount of Al$_{11}$RE$_3$ phase is 51/TA and the average length is 69.55 μm. Moreover, a generation model of Al$_{11}$RE$_3$ is established and the growth mechanism of Al$_{11}$RE$_3$ is analyzed. This work thus has proved that La/Nd ratio has a great effect on the microstructure and mechanical properties of AZ91.

1. Introduction

Magnesium alloys are the most promising lightweight material and are undoubtedly widely used in aeronautical, 3C, and automotive industries [1, 2]. The alloys have made significant inroads in interior parts as well as structural components [3, 4]. The most significant magnesium alloy application of automobiles utilizes AZ type casting alloys such as Mg-9 wt% Al-1 wt% Zn alloy (AZ91) [5]. AZ91 used in automobile offers good solidification characteristics of excellent fluidity and less susceptibility to hydrogen porosity so it is remarkably easy to cast [6]. Although AZ91 alloy was developed for a suitable combination of room-temperature strength with ductility and corrosion resistance, it’s poor high-temperature (> 120 °C) mechanical properties limit the automotive application of power train parts [7, 8]. Hence, it is reasonable to expect that there are high strength and low-cost alloys based on AZ91 alloy to be developed by alloying or micro-alloying [9].

Over the past decade, many investigators have been contributed for the modified-AZ91 alloy by alloying and micro-alloying elements, such as La, Ce, Nd, Y, Ca, B, Sr, Sb, Br, Pr and so on [10]. The results indicate that light rare earth elements (La, Ce and Nd) are more effective than other elements. The effect of rare earth elements to the as-cast microstructure of magnesium alloys is mainly reflected in the following aspects: (i) The addition of light rare earth elements can reduce the solid-liquid interfacial tension. The critical forming radius of the rare earth-containing magnesium alloy is reduced, and it is easy to nucleate, which promotes grain refinement of the alloy [11]. (ii) The partition coefficient of light rare earth in Mg is less than 1, and the solid solubility decreases with the decrease of temperature, so the rare earth element can increase the supercooling degree of the solid/liquid interface front component during solidification, which promotes the formation of completely divorced eutectic [12]. (iii) After the solidification process, some rare earth elements (like Nd) are dissolved in α-Mg,
which reduces the diffusion coefficient of solid solution, making it difficult to diffuse Al in α-Mg solid solution, thus inhibiting the secondary $\beta$-Mg$_{17}$Al$_{12}$ phase [13]. At the same time, the Al element in the alloy will be consumed during the formation of the stable phase of Al$_{11}$RE$_3$, which will reduce the number of eutectic $\beta$-Mg$_{17}$Al$_{12}$ and obtain finer dispersed particles [14].

Furthermore, Zhang et al [15] studied the mechanical properties of Mg-4Al-4La alloy and concluded that AlLa$_4$ exhibited excellent mechanical properties due to the hindrance to grain boundary sliding and dislocation motion provided by Al$_{11}$La$_3$ phase. Yang et al [16] reported that needle-like phase Al$_{11}$La$_3$ was thermodynamically stable in Mg-Al alloy at temperatures lower than 1000 K. Studies [17, 18] showed that Mg-4Zn alloy with addition of 1 wt% La exhibited good corrosion resistance and minor Nd significantly improved the tensile properties of ZK60 alloy. Arrabal et al [19] found that Nd refined $\beta$-phase morphology in AZ91 and improved the corrosion resistance. Chen et al [20] studied the effect of Nd on mechanical properties of rotary forging AZ71. It was concluded that mechanical properties reached the maximum value when added 1.0 wt% Nd to AZ71. In addition, Zengin et al [21] reported that the yield and ultimate tensile strengths of A4 (Mg-4 wt% Al) alloy were remarkably improved by addition of 1 wt% Ce/La. Xu et al [22] studied the addition of mischmetal (Ce, La, Pr, Nd) could enhance the mechanical properties because of the formation of Al-RE phase. Asl et al [23] reported that the presence of thermally stable Al$_{11}$RE$_3$ increased the mechanical properties of the AZ91 alloy at elevated temperatures. Bayani et al [24] showed that the mechanical properties and high-temperature properties of AZ91 alloy reached the maximum value with the addition of 2.0 wt% misch metal. However, the effect of different La/Nd ratio on microstructure and mechanical properties of Mg-Al alloys is not clear.

Therefore, the objective of the present study is to investigate the effects of La/Nd ratio on the microstructure, ambient and elevated compression properties of as-cast AZ91. The total amount of La and Nd added is kept constant at 2 wt% and the La/Nd ratio is variable. A generation model of Al$_{11}$RE$_3$ is established and the growth mechanism of Al$_{11}$RE$_3$ is analyzed.

### 2. Experiment procedure

The AZ91-xLa/Nd alloys were produced from the AZ91D ingot, Mg-12.8 wt% La and Mg-30 wt% Nd master alloys. The experimental alloys were melted and alloyed in a graphite crucible by an electric resistance furnace under a protection of SF$_6$ (1 vol%) and CO$_2$ (99 vol%) mixed gas atmosphere. At 750 °C, the molten metal was held for 30 min to make RE dissolved completely. The melt was refined by R1-2 flux and was held at 720 °C for 20 min. Then the melt was poured into a steel mold (10 mm in thickness) which was coated and preheated to 200 °C. The chemical compositions of AZ-xLa/Nd alloys (listed in Table 1) were tested using inductively coupled plasma method atomic emission spectroscopy (ICP-AES).

| Alloys | La (wt%) | Nd (wt%) | Al (wt%) | Zn (wt%) | Mn (wt%) | Si (wt%) | Mg (wt%) |
|--------|----------|----------|----------|----------|----------|----------|----------|
| I      | 0:0      | 0.00     | 6.89     | 0.74     | 0.18     | 0.054    | Bal.     |
| II     | 1:5      | 0.32     | 1.67     | 8.54     | 0.75     | 0.17     | 0.052    | Bal.     |
| III    | 1:3      | 0.51     | 1.49     | 8.66     | 0.73     | 0.16     | 0.051    | Bal.     |
| IV     | 2:3      | 0.77     | 1.21     | 8.48     | 0.75     | 0.17     | 0.053    | Bal.     |
| V      | 1:1      | 0.98     | 1.02     | 8.67     | 0.73     | 0.17     | 0.059    | Bal.     |
| VI     | 2:1      | 1.33     | 0.65     | 8.57     | 0.72     | 0.18     | 0.058    | Bal.     |

The microstructures of as-cast AZ91-xLa/Nd alloys were analyzed by scanning electron microscopy (SEM, FEI QUANTA-200) equipped with dispersive x-ray spectroscopy (EDX) operated at 20 kV. The specimens (10 mm × 10 mm × 20 mm) for SEM were cut from the ingots (80 mm × 100 mm × 10 mm) were polished using grades of polishing paper and then etched by 4% nitric acid in alcohol. The quantitative metallographic analysis (the amount and length) was conducted for each alloy by using SEM images with the Image-pro v5.0 software. The amount of needle-like phase is calculated from the true area (μm$^2$) of SEM micrographs (800 × 1000 μm$^2$). The phase identifications of experimental alloys were carried out by x-ray diffractometer (XRD) using Cu Kα radiation operated at 40 kV and 40 mA (K = 1.5418 Å). Samples (540 mm × 6 mm) for hardness testing were cut from the as-cast AZ91D-xLa/Nd alloys. The Brinell hardness of each specimen was measured with a 310HBS-3000 digital display hardness tester (HBSS/250/30). The average hardness of each sample was obtained from five tested values. Three cylindrical compression specimens (Φ10 mm × 25 mm) were machined from each alloy ingot to ensure the reproducibility of the data, and the compression tests were performed at a rate of 1 mm min$^{-1}$ on a WDW-200 electronic universal testing machine at room temperature (20 °C) and high temperature (150 °C).
3. Results

3.1. As-cast microstructure structure

Figure 1 shows the SEM images of the as-cast AZ91-xLa/Nd alloys. Figure 1(a) shows a typical microstructure of AZ91 alloy, and the grey zone indicated by $\alpha$ is Mg matrix. The coarse dark grey strip-shaped phase indicated by $\beta$ is $\beta$-Mg$_{17}$Al$_{12}$ which is evenly distributed along grain boundaries [25]. At room temperature, $\beta$ phase can improve the hardness and compression properties of magnesium alloys [26]. However, the application of magnesium alloys has been greatly limited due to their poor high-temperature properties [27]. Figures 1(b)–(f) show the presence of a large number of needle-like phases (indicated by R) and irregular block-like phases (indicated by $\beta$) in AZ91-xLa/Nd alloys. The $\beta$ phase becomes finer dispersed particle with the addition of La and Nd. The length and quantity of needle-like phase are different in AZ91-xLa/Nd alloys with increasing La/Nd ratio. Additionally, it is important to note that the white particulate phase marked by cycles, which emerges in AZ91 with RE addition.

In order to obtain information on the behavior of RE as well as on the distribution of Al and Zn in AZ91-xLa/Nd alloys, EDS area analysis was carried out and the results are shown in figure 2. The results clearly confirm that Al element concentrates on the needle-like phase and the block-like phase (figure 2(c)). La and Nd elements congregate in the needle-like phase and the white particulate phase (figure 2(d) and (e)). With respect to Zn, the segregation to the bulk phase is less pronounced, but still present (figure 2(f)).

Figure 3 shows the microstructures of different second phases in as-cast AZ91-xLa/Nd alloys imaged by backscatter electron (BSE) and corresponding EDS results. Figure 3(a) shows the elongate acicular phase and the irregular polygonal phase distribute along the boundary of the matrix. Uniform distribution of second phases in the cell boundaries may increase the mechanical properties effectively [28]. Figure 3(d) shows the EDS analysis of second phases marked by A, B, and C in figure 3(a). The EDS analysis result of A from figure 3(d) reveals the existence of the eutectic phase Mg$_{17}$Al$_{12}$ known as $\beta$ phase [29]. Figure 3(b) shows the micrograph of $\beta$-Mg$_{17}$Al$_{12}$ which has two kinds of morphologies, the laminar shaped one surrounding the irregular massive one [30]. Combining with the XRD patterns in figure 4 and the EDS results of B in figure 3(d), the needle-like phase shown in figure 3(a) could be deduced as Al$_{13}$RE$_5$ (Al$_{13}$La$_5$, Al$_{13}$Nd$_5$) [31]. The atomic ratio of Al:RE is slightly larger than 11:3 because x-rays penetrate the finer needle-like phase and $\beta$-Mg$_{17}$Al$_{12}$ is detected. The EDS result of C in figure 3(d) reveals the presence of Al$_2$RE which presents a typical white particulate morphology [32–34]. An EDS
A line scan was carried out along the linear segment marked in figure 3(c) and the results are shown in figure 3(e). The intensity scale of each element is adjusted to facilitate observation of the spectrum. The EDS line scan results are consistent and reconfirm that Zn concentrates in the bulk phase and needle phase area. During the
solidification, aluminum is enriched towards the periphery of grain due to the slow diffusion. In addition, the solidification process proceeds with the magnesium-rich end of the ternary phase diagram of Mg-Al-Zn alloy, resulting in segregation of Zn and Al in the residual liquid along grain boundary.

Figure 4 shows the XRD patterns of the as-cast alloys: Alloy I, II, IV, VI; (b) and (c) partial enlargement of the main peaks corresponding to Al11La3 and Al11Nd3.

Light rare earths (La, Ce, Pr, and Nd) have quite similar properties and can be referred to collectively as RE. But the formation of AlxREy is sensitive to individual rare-earth elements. Compared with Nd, La combines with Al more readily to form Al11La3 due to higher electronegativity difference with Al. As consequence, the number of Al11Nd3 phases in the AZ91-xLa/Nd alloys less than Al11La3 when the La/Nd ratio is more than 1/1.

Figure 5 shows the area fraction of β-phase. When La/Nd ratio is 1/1 (Alloy V), the area fraction of β-Mg17Al12 phase is the smallest, only 3.51%. It is indicated that the additions of La and Nd to AZ91-xLa/Nd alloys results in the great decrease of volume and size of β-Mg17Al12 phases. As the La/Nd ratio increases, the area fraction of β-Mg17Al12 phase decreased
significantly and then increased slightly. The morphology of $\beta$-Mg$_{17}$Al$_{12}$ phase becomes coarsen when the La/Nd ratio is greater than 1/1.

Figure 6 shows a statistical histogram of the quantity and length of the needle-like phase calculated from the TA of SEM micrographs in the AZ91D-xLa/Nd alloys. It is observed that La/Nd ratio has a strong influence on the quantity and length of the needle-like phase in the alloys. With increasing La/Nd ratio, the amount of needle-like phase in the alloy increases and its average length decreases. The amount increases as the La/Nd ratio increases from 0/0 to 1/1 and reaches the maximum when La/Nd ratio is 1/1. The amount decreases when La/Nd ratio is greater than 1/1. Besides, the longest length of needle-like phase in alloys increases as the La/Nd ratio increases from 0/0 to 2/3 and then decreases when the La/Nd ratio is greater than 2/3. The longest length reaches the maximum (300.18 $\mu$m) when the La/Nd ratio is 2/3. The average length of needle-like phase in alloys decreases from 78.13 $\mu$m to 68.42 $\mu$m as La/Nd ratio increases from 0/0 to 3/2.

3.2. Brinell hardness

Figure 7 shows the Brinell hardness of the AZ91D-xLa/Nd alloys. Brinell hardness decreases from 66.86 to 65.03 and then increases to the peak value of 67.10 as the La/Nd ratio increases from 0/0 to 2/3. As the La/Nd ratio increases from 2/3 to 3/2, Brinell hardness decreases again to the minimum value of 64.50. It is revealed that the needle-like phase has no significant improvement on the Brinell hardness at room temperature. This may be due to the great decrease of fine granular $\beta$-Mg$_{17}$Al$_{12}$ phase. Besides, needle-like phase with big size is hard to have

![Figure 6. Statistical histogram of Al$_{11}$RE$_3$ phase length of as-cast alloys: (a) Alloy II; (b) Alloy III; (c) Alloy IV; (d) Alloy V; (e) Alloy VI.](image-url)
contribution to hardness, as hardness testing depends on the nature of the constrained deformation around the indenter tip.

3.3. Compressive properties

Figure 8 shows the stress-strain curves of the as-cast alloys (a) at 20 °C and (b) at 150 °C obtained by the compression tests. It can be seen that AZ91-xLa/Nd alloys (with La and Nd added) exhibit superior compression strength and moderate elongation compared with AZ91 both at room temperature and high temperature. Besides, when the La/Nd is 2/1 (Alloys VI) shows higher ductility than other AZ91-xLa/Nd alloys. Liu [38] reported that the strength and elongation of Mg-4 wt% Al alloys may decrease with the increasing amount of coarse and brittle intermetallics. The high ductility of Alloys VI should be related to the shortest average length of the needle-phase. AZ91-xLa/Nd alloys containing short and fine AlxREy may increase strength and ductility.

Figure 9 shows the SEM micrographs of fractured surface and the macroscopic sample after compression. All the fractures of AZ91-xLa/Nd alloys exhibit the same typical characteristics: fractures occur in a direction of 45 ° from the axis. AZ91-xLa/Nd alloys show no obvious signs of softening in compression experience at 150 °C from the macroscopic images of the fracture. During the compression process, grains that cannot withstand the critical shear stress crack (figure 9(a)) at the grain boundaries on the sliding surface, and then expand to fracture. The fracture is characterized by cleavage steps (figure 9(a)) and cleavage rivers (figure 9(b)). Quasi-cleavage type fracture (shown in figures 9(c) and (d)), which blends cleavage facets with uneven surface and micropores caused by dimple rupture, indicates that plasticity of AZ91-xLa/Nd alloys is improved at 150 °C.

Figure 10 presents the compression results at room temperature (20 °C) and elevated temperature (150 °C). The compressive property at room temperature has been improved markedly as La/Nd ratio increases from 0/0.
In alloy II, a considerable number of β-Mg₁₇Al₁₂ phases and Al₁₁RE₃ phases strengthen the AZ91D-xLa/Nd alloys with a lower La/Nd ratio of 1/5 at room temperature. It is revealed that the interaction of β-Mg₁₇Al₁₂ phases and Al₁₁RE₃ phases strengthen the compression properties of the alloys at room temperature. Fine β-Mg₁₇Al₁₂ phases and a right amount of Al₁₁RE₃ phase distributed around the grain can strengthen the alloy for their effective impediment to grain boundary sliding. The compressive property (20°C) decreases from 363 MPa to 337 MPa as La/Nd ratio increases from 1/5 to 1/3 due to the great reduction of β-Mg₁₇Al₁₂ phases and only a few increase of Al₁₁RE₃ phases. As La/Nd ratio increases from 1/3 to 1/1, the compressive property increases to a peak value of 364 MPa. Meanwhile, the fraction of β-Mg₁₇Al₁₂ phases continuously decreases and the number of Al₁₁RE₃ phases increases. It suggested that the strengthening effect of Al₁₁RE₃ phases increases as the number increases. The compressive property (20°C) decreases again (in Alloy VI) when La/Nd ratio is greater than 1/1. Because the amount of Al₁₁RE₃ phase increases significantly than the other alloys and the morphology of β-Mg₁₇Al₁₂ phases coarsens slightly in Alloy VI. However, massive Al₁₁RE₃ phases will cause the matrix to be split significantly and deteriorate the compressive properties. The compressive properties of AZ91 alloy reach the peak value under the condition of La and Nd added with a right La/Nd ratio.

The compressive property at elevated temperature increases from 274 MPa to 330 MPa as La/Nd increases from 0/0 to 2/3 and decreases from 330 MPa to 318 MPa as La/Nd ratio increases from 2/3 to 2/1. When La/Nd ratio is 2/3, the compressive property at 150°C reaches an optimal value. The β-Mg₁₇Al₁₂ phases strengthen the Mg-Al alloys effectively at room temperature, but the strengthening effect is weakened at elevated
temperature since the softening and coarsening of the $\beta$-Mg$_{17}$Al$_{12}$ phases [27]. The needle-like phases (Al$_{13}$RE$_3$) are very effective in strengthening Mg-Al alloys at elevated temperatures for their thermodynamically stableness [16, 39]. The needle-like phases disperse with the right number and average length at grain boundaries and in the interiors of grains, which hinder the grain boundary sliding and harden the alloys [15]. Too many needle-like phases will cause the matrix to be split and induce the deterioration of the compressive properties. Therefore, AZ91D-xLa/Nd alloys exhibit excellent mechanical properties only on a condition of balanced mass ratio at La/Nd.

### 4. Discussion

The analysis above has been proved that La/Nd ratio has a strong influence on the phase morphology and mechanical properties of the AZ91D-xLa/Nd alloys. The addition of the rare earth elements La and Nd forms the thermally stable phase of Al$_{13}$La$_3$ and Al$_{13}$Nd$_3$ due to the difference in electronegativity between the elements. The electronegativity and electronegativity difference of the La, Nd, Mg and Al elements are listed in Table 2 [20, 40, 41]. Rare earth elements are more easily combined with Al to form thermally stable intermetallic compounds with La and Nd addition since the difference of electronegativity between La, Nd, and Al is greater than the difference of electronegativity with Mg. In addition, the Al-rich rare earth compounds process the same crystallization behavior because they are isostructural with other Al-RE compounds during the solidification process [42, 43]. At the same time, in the agglomerated region of Al, Mg elements, $\beta$-Mg$_{17}$Al$_{12}$ is still generated.

The addition of La and Nd causes intensive constitutional supercooling in front of the solid/liquid interface, promoting the primary $\alpha$-Mg phase solidification and enriching the Al elements in the amorphous liquid [44]. Meanwhile, the concentration of La, Nd and Al increases and restricts the growth of eutectic $\beta$-Mg$_{17}$Al$_{12}$ phases [39, 45, 46]. A possible mechanism of the formation of the Al$_{13}$RE$_3$ phases and $\beta$-Mg$_{17}$Al$_{12}$ phases could be proposed and described briefly below.

Case I: For AZ91D-xLa/Nd alloys with lower La/Nd ratios ($< 2/3$), the amorphous region is similar to region I (figure 11(a)). It would be easy to form a large aggregative zone of Nd and a small cluster of La since the content of Nd in region I is higher than La. Meanwhile, a scarce region of rare earth elements is formed around the large aggregative zone of Nd. Nd combines with Al to form Al$_{13}$Nd$_3$ and stops the growth when Nd is exhausted without adequate supplement. The small cluster of La would generate Al$_{13}$La$_3$ and stops the growth when La is exhausted. The needle-like phases grow short in length and less in quantity in this case.

Case II: For AZ91D-xLa/Nd alloys with higher La/Nd ratios (2v3 3v2), the amorphous region is similar to region II (figure 11(b)). There are many La, Nd clusters with suitable size in the melt of region II. Al$_{13}$Nd$_3$ is generated first probably and an appropriate amount of La in the alloy would be replenished to the cluster of Nd when Nd is exhausted. When La is exhausted, it would be supplemented with an appropriate amount of Nd and would be continuing to grow. In this case, needle-like phases grow up sufficiently to considerable long size and much number.

Case III: Case III with great La/Nd ($= 2/1$) is similar to Case I. In this case, as shown in region III (figure 11(c)), it would form a large aggregative zone of La and a small cluster of Nd. A scarce region of rare earth elements is formed around the large aggregative zone of La. La combines with Al to form Al$_{13}$La$_3$ and stops the growth when La is exhausted without supplement adequately. The small cluster of La generates Al$_{13}$La$_3$ and stops growing when La is depleted.

Case IV: The amorphous region of AZ91D-xLa/Nd alloys would include some regions like region IV (figure 11(d)). La and Nd in these regions accumulate inside the matrix and the formation of the needle-shaped phase in combination with the Al element along the boundary would grow from the periphery toward the center. The needle-like phases may grow throughout the entire grain.

Case V: The growth of $\beta$-Mg$_{17}$Al$_{12}$ phase in the amorphous region is similar to region V (figure 11(e)). Al combined with Mg around the boundary of the matrix would generate $\beta$-Mg$_{17}$Al$_{12}$ phase with a limited average size because of the consumption of Al with rare earths.

| Table 2. Electronegativity and electronegativity differences with Mg and Al of elements in alloys. |
|---------------------------------------|------------------|-------------------|-------------------|
| Element | Electronegativity | Electronegativity difference with Mg | Electronegativity difference with Al |
|----------|-------------------|-----------------------------------|-----------------------------------|
| La       | 1.10              | 0.21                             | 0.51                             |
| Nd       | 1.14              | 0.17                             | 0.47                             |
| Mg       | 1.31              | 0.00                             | 0.30                             |
| Al       | 1.61              | 0.30                             | 0.00                             |

Mater. Res. Express 7 (2020) 026531
As discussed above, the microstructure of amorphous region would crystallize into a petal-like morphology shown in figure 11(f). The growth mechanism theory is verified by figure 11(f).

5. Conclusions

(1) The La/Nd mass ratio has an effect on the microstructure of AZ91D. With increasing La/Nd ratio, \( \beta \)-Mg\(_{17}\)Al\(_{12}\) phases in AZ91D alloys become fine and discrete. Moreover, the area fraction of \( \beta \)-Mg\(_{17}\)Al\(_{12}\) phases decreases greatly and then increases slightly. When La/Nd ratio is 1/1, the area fraction of \( \beta \)-Mg\(_{17}\)Al\(_{12}\) phase is the smallest, only 3.51%.

(2) The number and length of needle-like phases varied with increasing La/Nd ratio. The number of needle-like phases increases from 33 to 80 as La/Nd ratio increases from 1/5 to 2/1. The average length of needle-like phase in alloys decreases from 78.13 \( \mu\)m to 68.42 \( \mu\)m as La/Nd ratio increases from 0/0 to 3/2.

(3) AZ91D-xLa/Nd alloys exhibit excellent mechanical properties only on a condition of a balanced mass ratio of La/Nd. Brinell hardness decreases from 66.86 to 65.03 and then increases to the peak value of 67.10 as the La/Nd ratio increases from 0/0 to 2/3. As the La/Nd ratio increases from 2/3 to 3/2, Brinell hardness decreases again to the minimum value of 64.50.

(4) The compressive property (20 °C) has been improved markedly as La/Nd ratio increases from 0/0 to 1/5. As La/Nd ratio increases from 1/5 to 1/3, the compressive property (20 °C) decreases from 363 MPa to 337 MPa. As La/Nd ratio increases from 1/3 to 1/1, the compressive property increases to a peak value of 364 MPa. The compressive property at elevated temperature increases from 274 MPa to 330 MPa as La/Nd increases from 0/0 to 2/3 and decreases from 330 MPa to 318 MPa as La/Nd ratio increases from 2/3 to 2/1. When La/Nd ratio is 2/3, the compressive property at 150 °C reaches an optimal value.

Acknowledgments

This study was financially supported by National Natural Science Foundation of China (Grant number 51574100 and 51701087) and National Key Research and Development Program (2019YFB2006500).

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References

[1] Luo A and Pekguleruyz M 1994 Cast magnesium alloys for elevated temperature applications J. Mater. Sci. 29 5259–71
[2] Mordike B and Ebert T 2001 Magnesium: properties-applications-potential Mater. Sci. Eng. A 302 37–45
[3] Luo A A 2013 Magnesium casting technology for structural applications J. Magnes. Alloys 1 2–22
[4] Kulecki M K 2008 Magnesium and its alloys applications in automotive industry Int. J. Adv. Manuf. Technol. 39 831–65
[5] Pekguleruyz M O and Kaya A A 2003 Creep resistant magnesium alloys for powertrain applications Adv. Eng. Mater. 5 866–78
[6] Desch C 1937 Magnesium alloys The Aeronautical Journal 41 369–82
[7] Polmeart I 1994 Magnesium alloys and applications Mater. Sci. Technol. 10 1–16
[8] Luo A, Zhang C and Sachdev A 2012 Effect of eutectic temperature on the extrudability of magnesium–aluminum alloys Script. Mater. 66 491–4
[9] Lee S, Lee S H and Kim D H 1998 Effect of Y, Sr, and Nd additions on the microstructure and microfracture mechanism of squeeze–cast AZ91-x magnesium alloys Metall. Mater. Trans. A 29 1221–35
[10] Pan F, Yang M and Chen X 2016 A review on casting magnesium alloys: modification of commercial alloys and development of new Alloys Mater. Sci. Technol. 32 1211–21
[11] Ying L, Weiping C and Weiwen Z 2004 Effects of re on microstructures and mechanical properties of hot-extruded AZ31 magnesium alloy J. Rare Earths 22 527–32
[12] Fang X Y, Yi D Q and Bin W 2006 Effect of yttrium on microstructures and mechanical properties of hot rolled AZ61 wrought magnesium alloy Trans. Nonfer. Met. Soc. China 16 1053–8
[13] Zhang J, Wang J and Qiu X 2008 Effect of Nd on the microstructure, mechanical properties and corrosion behavior of die-cast Mg–4Al-based alloy J. Alloys Comp. 509 1069–78
[14] Liu Y, Yang Q and Zeng X 2000 Effects of rare earths on the microstructure, properties and fracture behavior of Mg–Al alloys Mater. Sci. Eng. A 278 66–76
[15] Zhang I, Yu P and Liu K 2009 Effect of substituting cerium-rich mischmetal with lanthanum on microstructure and mechanical properties of die-cast Mg–Al–RE alloys Mater. Des. 30 2372–8
[16] Yang Q, Liu X and Bu F 2015 First-principles phase stability and elastic properties of Al–La binary system intermetallic compounds Intermetallics 60 92–7
[17] Zengin H, Turen Y and Atlaltci H 2018 Microstructure, mechanical properties and corrosion resistance of as-cast and as-extruded Mg-4Zn–1Al magnesium alloy Rare Met. 1–9
[18] Zengin H, Turen Y and Turan M F 2019 Tensile and wear properties of as-cast and as-extruded ZK60 magnesium alloys containing minor Nd additions Mater. Res. Exp. 6 1–10
[19] Arrabal R, Mingo B and Pardo A 2015 Role of alloyed nd in the microstructure and atmospheric corrosion of as-cast magnesium alloy AZ91 Corros. Sci. 97 38–48
[20] Chen J K, Chen Y C and Hsien-Tsung L I 2015 Effects of Nd and rotary forging on mechanical properties of AZ71 mg alloys Trans. Nonfer. Met. Soc. China 25 3232–31
[21] Zengin H, Turen Y and Elen L 2019 A comparative study on microstructure, mechanical and tribological properties of A4, AE41, AS41 and AJ41 magnesium alloys J. Mater. Eng. Perform. 28 4647–57
[22] Xu Y, Zhang K and Jain L 2016 Effect of mischmetal on mechanical properties and microstructure of die-cast magnesium alloy AZ91D J. Rare Earths 34 742–6
[23] Asl K M, Masoudi A and Khomamizadeh F 2010 The effect of different rare earth elements content on microstructure, mechanical and wear behavior of Mg–Al–Zn alloy Mater. Sci. Eng. A 527 2027–35
[24] Bayani H and Saebnoori E 2009 Effect of rare earth elements addition on thermal fatigue behaviors of AZ91 magnesium alloy J. Rare Earths 27 253–8
[25] Tan Q, Mo N and Jiang B 2017 Combined influence of be and Ca on improving the high-temperature oxidation resistance of the magnesium alloy Mg–Al–Zn Corros. Sci. 122 1–11
[26] Du W, Sun Y and Min X 2003 Microstructure and mechanical properties of Mg–Al based alloy with calcium and rare earth additions Mater. Sci. Eng. A 356 1–7
[27] Che C, Cai Z and Yang X 2017 The effect of co-addition of Si, Ca and RE on microstructure and tensile properties of as-extruded AZ91 alloy Mater. Sci. Eng. A 705 282–90
[28] Yang Q, Zheng T and Zhang D 2013 Microstructures and tensile properties of Mg-4Al-4La-0.4Mn-xB (x = 0, 0.01, 0.02, 0.03) alloy J. Alloys Comp. 572 129–36
[29] Roodposhti P S, Sarkar A and Murty K L 2016 Grain boundary sliding mechanism during high temperature deformation of AZ31 magnesium alloy Mater. Sci. Eng. A 669 171–7
[30] Asl K M, Tari A and Khomamizadeh F 2009 The effect of different content of Al, RE and Si element on the microstructure, mechanical and creep properties of Mg–Al alloys Mater. Sci. Eng. A 523 1–6
[31] Zhou H T, Zeng X Q and Dting W J 2004 Effect of La and Nd on microstructures and mechanical properties of AZ61 wrought magnesium alloy Trans. Nonfer. Met. Soc. China 14 67–70
[32] Powell B R, Rezhtes V and Balogh MP 2016 Essential Readings in Magnesium Technology (Berlin: Springer) 275–81
[33] Zhang J, Zhang M and Meng J 2010 Microstructures and mechanical properties of heat-resistant high-pressure die-cast Mg–4Al–xLa–0.3 Mn (x = 1, 2, 4, 6) alloys Mater. Sci. Eng. A 527 2527–37
[34] Su M, Zhang J and Feng Y 2017 Al–Nd intermetallic phase stability and its effects on mechanical properties and corrosion resistance of HPDC Mg–4Al–4Nd–0.2 Mn alloy J. Alloys Comp. 691 643–64
[35] Tamura Y, Kida Y and Tamehori H 2008 The effect of manganese on the precipitation of Mg17Al12 phase in magnesium alloy AZ91 J. Mater. Sci. 43 1249–58
[36] Powell B R, Rezhtes V and Balogh MP 2002 Microstructure and creep behavior in AE42 magnesium die-casting alloy JOM 54 34–8
[37] Zhang J, Liu K and Fang D 2009 Microstructure, tensile properties, and creep behavior of high-pressure die-cast Mg–4Al–4RE–0.4 Mn (re = la, ce) alloys J. Mater. Sci. 44 2046–54
[38] Liu Y, Jia X and Xiao Q 2019 Effect of la on microstructure, thermal conductivity and mechanical properties of Mg–4Al magnesium alloys J. Alloys Comp. 806 71–8
[39] Wang J, Wu Y and Zhang H 2008 Microstructures and mechanical properties of as-cast Mg–5Al–0.4 Mn–xNd (x = 0, 1, 2 and 4) alloys Mater. Sci. Eng. A 472 352–7
[40] Zhang S G, Wei B K and Cai Q Z 2003 Effect of mischmetal and yttrium on microstructures and mechanical properties of Mg–Al alloy Trans. Nonfer. Met. Soc. China 13 83–7
[41] Wang J, Wang L and An J 2008 Microstructure and elevated temperature properties of die-cast AZ91- x Nd magnesium alloys J. Mater. Eng. Perform. 17 725–9
[42] Fang X, Lü S and Wang J 2017 Effects of cer/la misch metal content on microstructure evolution and mechanical properties of Mg–Zn–Y alloy Mater. Sci. Eng. A 699 1–9
[43] Wei L Y and Dunlop G L 1996 The solidification behaviour of Mg–Al–rare earth alloys J. Alloys Comp. 232 264–8
[44] Murray J L 1982 The Al–Mg (aluminum – magnesium) system J. Phase Equilibria 3 60
[45] Mahmudi R and Moeendarbari S 2013 Effects of Sn additions on the microstructure and impression creep behavior of AZ91 magnesium alloy Mater. Sci. Eng. A 566 30–9
[46] Pettersen G, Westengen H and Høier R 1996 Microstructure of a pressure die cast magnesium—4wt% aluminium alloy modified with rare earth additions Mater. Sci. Eng. A 207 115–20