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ARTICLE

Effects of Nd on Microstructures and Mechanical Properties of AM60 Magnesium Alloy in Vacuum Melting

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Abstract: The microstructure changes brought by the addition of Nd element to AM60 magnesium alloy were studied, the precipitating phases were identified and their influences on the mechanical properties of alloys were investigated. Results show that Nd addition makes the refinement of microstructure of the AM60 alloy, and decreases the size of $Mg_{17}Al_{12}$ phase. Nd element takes a priority to react with Al element over Mg, Mn and Zn forming binary phase $Al_{11}Nd_3$ with high melting point. Certain content of Nd can increase tensile strength, yield strength and elongation of the alloy. But with too much addition, Nd would combine with more Al in matrix and decrease strengthening effect because $Al_{11}Nd_3$ phase would become coarsening. The mechanical property tests indicate that AM60-0.9Nd alloy has the best properties. Maximum tensile strength, maximum yield strength, maximum elongation are 230 MPa, 127 MPa and 14% respectively, increased by 28%, 48% and 250% respectively.

Key words: magnesium alloy; AM60 alloy; Nd; microstructure; mechanical properties

Magnesium alloys, as the lightest structural metal, are called green-engineering material in the 21st century with great development potential in automobile, electronics and aerospace industries because of their high specific strength and stiffness, superior damping capacity, good electromagnetic shielding characteristics, excellent shock absorption and good machinability[1-3]. Since they can satisfy the need of weight saving, fuel economizing and reducing emission of CO_2, magnesium alloys have been used to fabricate a variety of automobile parts, such as automobile wheel hubs, instrument panels, and steering wheels[4]. The applications of the most common magnesium alloys, such as AZ91 and AM60, account for 90% of total automobile magnesium alloys[5]. The ductility of AM60 alloy is better than that of AZ91, but the strength of AM60 is lower. In order to satisfy the properties of automobile wheel hubs, it is exigent to improve the mechanical properties of AM60 alloy.

At present, a variety of methods have been developed to refine magnesium-aluminum alloys, such as superheating, the Elfinal process, the addition of carbon or particles (Al_4C_3, AlN, SiC, TiC); of these methods, the addition of $FeCl_3$ offers practical advantages because of the low operating temperature involved. However, the problem of this method is the emission of harmful chloride gas; and the chloride and Fe remaining in the magnesium alloys will cause severe corrosion[6,7]. Nd has many merits such as purifying alloy melt, modifying castability, refining the microstructure, improving the mechanical properties and anti-oxidization properties. In addition, our country is rich in magnesium resource and RE resource, so it is important to study high-property magnesium with RE[8-11]. However, study on the effects of Nd addition on mechanical properties of AM60 magnesium alloy is very limited. There is a very few of study on the smelting of AM60 alloy in vacuum.

In this study, to avoid the pollution caused by air and fusing agent in the process of smelting, the sample of magnesium alloy was smelted by adding Nd in Ar vacuum. The microstructures and mechanical properties tests were carried out by adopting 5 kinds of AM60 alloys with different Nd contents at room temperature and the effects of Nd were discussed. The results of this study will provide a reference to understand the effects of Nd on AM60 alloy and extend magnesium alloy application areas.

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1 Experiment

Mg, Al, and Zn were used as starting materials to prepare the AM60 alloy. Based on AM60 alloys, four Nd containing alloys were developed. Nd contents were in the range from 0.3% to 1.2%(mass fraction). The design composition of samples and the results of SPARKLAB and ICP testing are listed in Table 1.

The alloys were smelted and refined in ZRR-M10 vacuum resistance melting furnace, and the following is the details of the experiment. a) The sidewall of the furnace and non-corrosive steel crucible were cleaned, into which the starting materials were put, and the coated Nd powder was put into the alloy storehouse. b) The melting system was pumped to 10^{-3} Pa, and Ar was filled into the furnace. c) When Ar was filled up to 10^{2}Pa, the vacuum valve was shut. d) When the starting materials were heated up to 800±5 °C, the Nd powder was added, and after the materials were stirred thoroughly, deposited for 18-20 min to refine magnesium alloy. e) At the temperature of 680±5 °C, the alloy was cast. f) When the cast alloy was cooled, the furnace was opened, and the samples taken from the cast were used for analyzing and testing.

The compositions of samples were analyzed by SPARKLAB, and the content of Nd was measured by IRIS Intrepid Ⅱ(ICP). The microstructure and morphologies of the secondary phases were characterized by field emission scanning electron microscope (FESEM, JSM-6700F) and optical microscope (NIKON 1500). Phase analysis was carried out by X-ray diffractometer (RAX-10), and the tensile properties test were conducted at room temperature by WDW-100KN stretcher.

Table 1 Chemical composition of experimental alloys

Alloy		Designation and actually composition/% (mass fraction)				
		Al	Mn	Zn	Nd	Mg
No.1	Before	6	0.35	0.2	---	Bal.
	After	6.04	0.381	0.207	---	Bal.
No.2	Before	6	0.35	0.2	0.3	Bal.
	After	5.81	0.343	0.201	0.289	Bal.
No.3	Before	6	0.35	0.2	0.6	Bal.
	After	5.80	0.321	0.220	0.594	Bal.
No.4	Before	6	0.35	0.2	0.9	Bal.
	After	5.83	0.329	0.217	0.899	Bal.
No.5	Before	6	0.35	0.2	1.2	Bal.
	After	5.79	0.336	0.139	1.186	Bal.

2 Results

2.1 Effects of Nd content on microstructure

The optical microstructures of the as-cast AM60, AM60-0.6Nd, AM60-0.9Nd, AM60-1.2Nd alloy are shown in Fig.1a, b, c, d, respectively. XRD pattern of AM60 indicates that this alloy is mainly composed of α-Mg and $Mg_{17}Al_{12}$ phase (Fig.2a). Some cramp discontinuous lumps are distributed in the boundary area and SEM observation indicates a divorced eutectic characteristic, as can be seen from Fig.3a. EDS analysis reveals AM60 is mainly composed of Mg and Al elements (Fig.3d), and $Mg_{17}Al_{12}$ is confirmed. SEM observation also shows some particles in the α-Mg, EDS results indicate that they are Al-Mn phase[12] (Fig.3e), which frequently appear in AM60 alloy in normal form, like particle and square. Fig.1b, c, d show the optical microstructures of the as-cast AM60 alloys with different contents of Nd. It can be seen that the grains of alloys can be refined and the volume and size of β-$Mg_{17}Al_{12}$ are decreased in the as-cast microstructure by adding Nd element. A typical microstructure of AM60-0.9Nd is revealed in Fig.1c. The XRD indicates the as-cast microstructure of AM60-0.9Nd alloy is mainly composed of α phase, $Mg_{17}Al_{12}$ and $Al_{11}Nd_3$ phase (Fig.2b). Some polygon particles and a few needle-shaped particles emerge in the matrix as a result of the addition of about 0.9%(mass fraction) Nd. Some polygon and rod-like particles are occasionally found in the microstructure, according to the results of XRD and EDS analysis its chemical formula is $Al_{11}Nd_3$ (Fig.3e). The further increase of Nd content leads to larger β phase in the microstructure of AM60 alloy, shown in Fig.1d), and more needle-shaped particle appear in this alloy (Fig.3c).

2.2 Effects of Nd content on tensile properties at room-temperature

The as-cast yield strength, ultimate tensile strength and total elongation of the five alloys are shown in Fig.4. The tensile test results indicate that the Nd addition is beneficial to the improvement of elongation, as shown in Fig.4. The elongation attains the maximum value of 14% when the Nd content is up to 0.9%(mass fraction). Further increase of Nd content

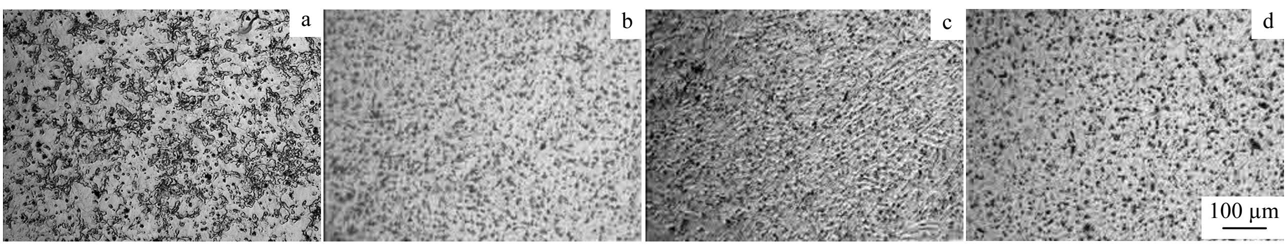

Fig.1 Optical microstructures of the cast alloy: (a) AM60; (b) AM60-0.6 Nd; (c) AM60-0.9 Nd; and (d) AM60-1.2 Nd

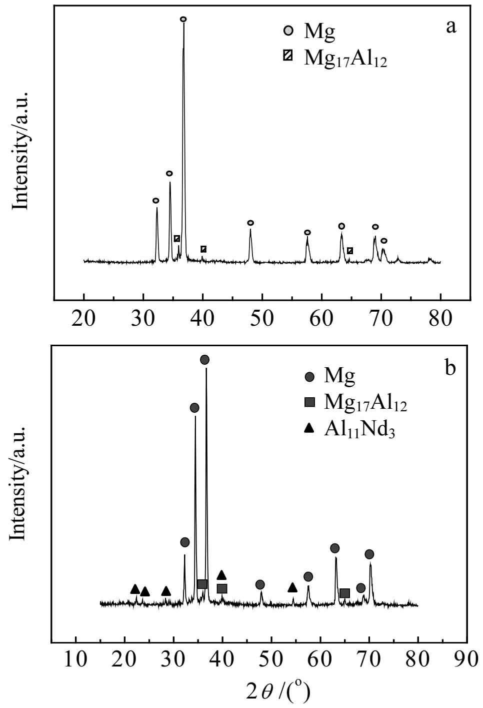

Fig.2 X-ray diffraction patterns: (a)AM60 and (b)AM60-0.9Nd

will lead to the decrease of elongation. The effect of Nd element on the ultimate tensile strength and the yield strength seems to be consistent with that on the elongation. The addition of about 0.9% (mass fraction) Nd leads to the maximum ultimate tensile strength and yield strength value, which 230 MPa and 127 MPa respectively. Compared with AM60 alloy, AM60-0.9Nd alloy shows an increment magnitude with about 50 MPa for the ultimate tensile strength, and about 40 MPa for the yield strength. Further increase of Nd content leads to dropping trend of the ultimate tensile strength and the yield strength, but the decrease of the yield strength is not so obvious.

2.3 Effects of Nd content on tensile fracture

Magnesium alloy has a hcp structure, whose failure usually takes on brittleness through cleavage or quasi-cleavage fracture[13]. Fig.5a, b, c, d show SEM images of tensile fractographs at room temperature for AM60, AM60-0.6Nd, AM60-0.9Nd, AM60-1.2Nd, respectively. Fig.5a is the image of AM60 alloy, which shows the well-developed river pattern and distinct cleavage steps. Fig.5b, c, d indicate that the addition of Nd in the AM60 alloy causes plenty of tearing ridges, tiny dimples and cleavage steps on the tensile fractures of the samples. The addition of Nd changes the β-$Mg_{17}Al_{12}$ (cubic structure) into thin, dense and non-continuous phase, and plenty of tearing ridges and tiny dimples appeared on the tensile fractures resulting in increasing of the ductility and toughness. So, the AM60 alloy has better ductility and toughness by adding Nd element.

3 Discussion

When Nd element is added into AM60 alloy, great effects of Nd element on the solidification behavior of the alloy can be found, as Nd element is possessed of characteristics of big atom size and slow diffusion rate .In the process of solidifica-

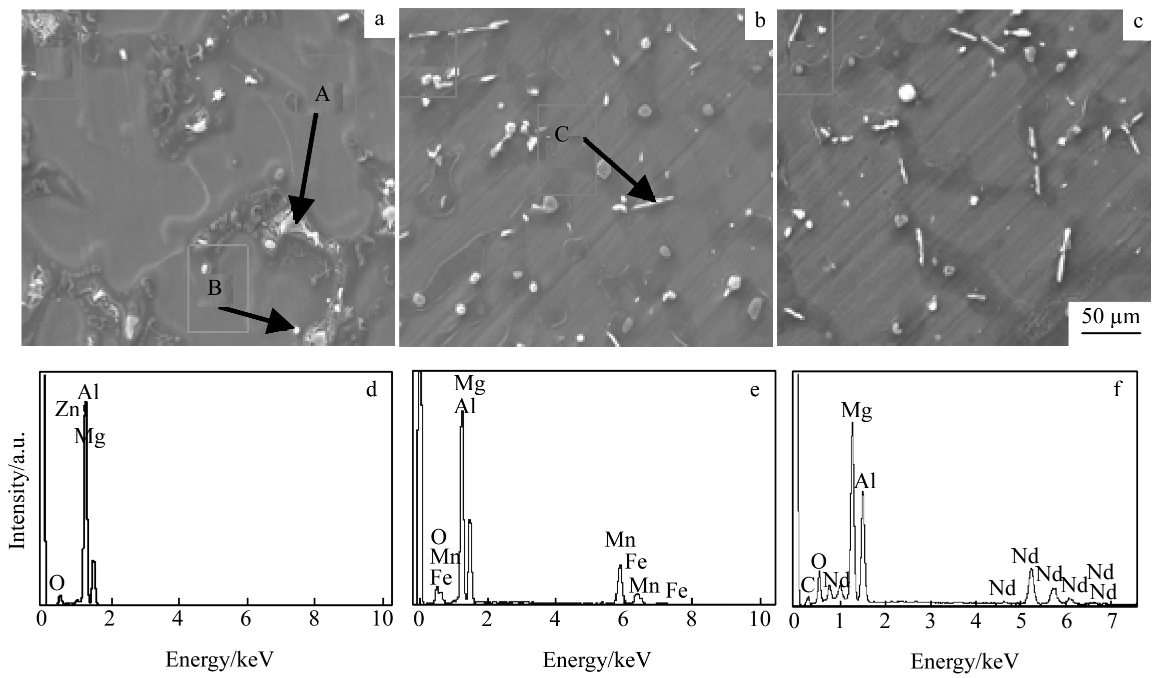

Fig.3 SEM images AM60 alloy: (a) AM60 alloy; (b) AM60-0.9 Nd; (c) AM60-1.2 Nd; (d) EDS of point A; (e) EDS of point B; and (f) EDS of point C

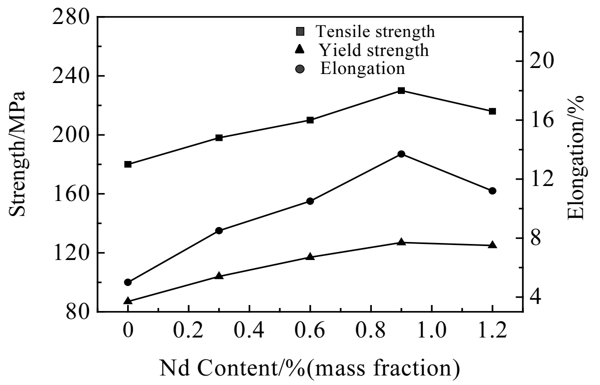

Fig.4 The relationship between the room-temperature tensile properties and Nd content in as-cast alloy

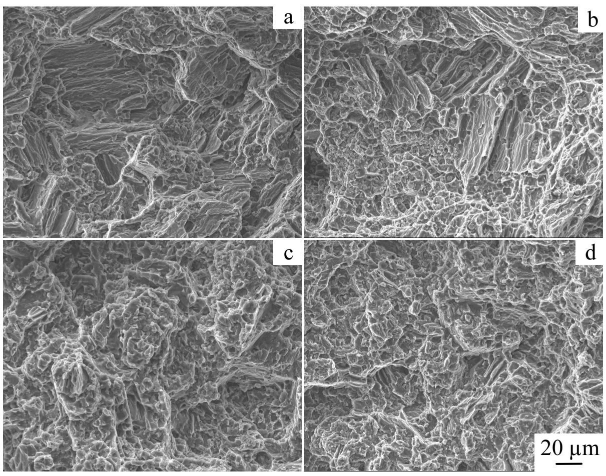

Fig.5 Tensile fracture micrographs of AM60 alloys: (a)AM60; (b)AM60-0.6 Nd; (c) AM60-0.9 Nd; and (d) AM60-1.2 Nd

tion, the solution elements such as Nd and Al will be separated from the primary α-Mg , and be concentrated at the solid/ liquid interface; thus constitutional under-cooling will appear in the diffusion layer ahead of the advancing solid/ liquid interface , and grain growth is restricted because the diffusion of the solute occurs slowly. Therefore, the as-cast microstructure can be refined by adding of RE elements. The compound phase with Nd element can be formed from the residual melt, in which Nd and Al elements are enriched after the solidification of the primary α-Mg. The $Al_{11}Nd_3$ phase will be formed prior to appearing of the β-$Mg_{17}Al_{12}$ phase on the grain boundary, because its formation temperature is about 150 °C higher than that of β-$Mg_{17}Al_{12}$ phase. The size of β-$Mg_{17}Al_{12}$ can be decreased by the precipitation of $Al_{11}Nd_3$ phase.

In the present work, the addition of Nd can greatly improve tensile properties of AM60 alloys at ambient temperature. The main strengthening mechanisms include: solid solution strengthening, fine-grained strengthening and second phase strengthening. The morphologies of the alloys also have effect on the tensile properties[14]. (1) Concerning refinement strengthening, grain size has great effect on mechanical properties. Addition of Nd has great effect on the refinement of microstructure, because the size of β-$Mg_{17}Al_{12}$ phase decreases. So the tensile properties of AM60 alloy are much improved. (2) Concerning solid solution strengthening, solid solubility of Nd in magnesium alloy is higher. After Nd is solved in Mg matrix phase, the solute atoms lead to non-spherical symmetrical distortion, so Nd also has great effect on the mechanical properties of magnesium alloy than any other RE elements. (3) Concerning second-phase strengthening, the granular particles are in favor of the tensile properties, while the needle-shaped particles do harm to the tensile properties because of the easy crack formation caused by the stress concentration between the interface of the particle and the matrix. When Nd element is added into AM60 alloy, the size of β-$Mg_{17}Al_{12}$ can be decreased, and the β-$Mg_{17}Al_{12}$ particles will be turned into fine spherical particles and their distribution became uniform. The discontinuous precipitation of $Mg_{17}Al_{12}$ phases is effectively suppressed because it has deleterious effect on mechanical properties of Mg-Al alloys[15]. So the addition of trace Nd can improve the mechanical properties. In addition, precipitation of $Al_{11}Nd_3$ phase has a beneficial effect on mechanical properties of magnesium alloy, but the $Al_{11}Nd_3$ phase with a tapering morphology in 1.2% RE-containing AM60 alloy is detrimental to the tensile properties in despite of the relatively uniform distribution. The conclusion can be drawn that the combination effect of the above mentioned strengthening mechanisms will bring AM60 alloy the great improvement of mechanical properties.

4 Conclusion

1) The as-cast microstructure of AM60 alloy is mainly composed of α-Mg and $Mg_{17}Al_{12}$ phase. Addition of Nd is much beneficial to refining the microstructure of AM60 alloy, and at the same time causes a morphological change in $Mg_{17}Al_{12}$ particles from discontinuous precipitation to small polygonal type, resulting in the decrease of size of β-$Mg_{17}Al_{12}$.

2) AM60 has the best properties when the addition of Nd is 0.9%(mass fraction), but further increase of Nd content will lead to the decreased of properties.

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真空条件下Nd对AM60镁合金组织与性能的影响

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摘　要：研究了稀土 Nd 对 AM60 镁合金组织的影响，并分析析出相及其对合金力学性能的影响。结果表明，在 AM60 合金中加入稀土 Nd 元素能有效地细化合金组织，使 $Mg_{17}Al_{12}$ 相分离变细；Nd 元素优先与合金中的 Al 元素反应生成二元高熔点 $Al_{11}Nd_3$ 相；适量的稀土 Nd 能有效提高合金的抗拉强度、屈服强度和延伸率；过量的稀土 Nd 则会消耗合金中更多的 Al 元素和导致 $Al_{11}Nd_3$ 相粗化，使合金的力学性能下降；力学性能测试结果表明，AM60-0.9Nd 具有最高的抗拉强度(230 MPa)、最高的屈服强度(127 MPa)和最高延伸率(14%)，分别比基体合金提高 28%、48%和 250%。

关键词：镁合金；AM60 合金；Nd；微观组织；力学性能

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