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ARTICLE

Microstructure, Mechanical Properties and Electromagnetic Shielding Effectiveness of Mg-Y-Zr-Nd Alloy

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Abstract: The as-cast Mg-Y-Zr-*x*Nd alloys with different Nd contents were prepared, and the effects of Nd content on microstructure, mechanical properties and electromagnetic interference (EMI) shielding properties were investigated. The results show that the grain sizes are refined from 70.1 μm to 45.2 μm, discontinuous bone-shaped β phases are formed mostly in the triple junction of grain boundaries when the content of Nd increases to 2.63 wt%. The mechanical properties and EMI shielding capacity are both enhanced significantly by adding Nd element. The alloy with 2.63 wt% Nd has a good combination of mechanical properties and EMI properties. T6 heat treatment is able to further improve the EMI shielding effectiveness. The above-mentioned experiment results are attributed to the microstructural variation caused by adding different contents of Nd.

Key words: Mg-Y-Zr-Nd alloy; microstructure; mechanical properties; EMI shielding property

With the rapid development of science and technology, the wireless devices such as the GSM and UMTS towers, radar systems, mobile phones, computers, GPS systems and other electronics-based products are used widely[1-3]. The electromagnetic (EM) radiation emitted by these devices can cause health problems such as nervousness, insomnia, languidness, and headaches. The accurate, reliable and safe outputs are also suffering from unwanted electromagnetic interference (EMI) from other communication systems[4,5]. So effective EMI shielding materials are required to diminish the damage of electromagnetic radiation.

Metals are by far the most common materials for EMI shielding due to their higher electrical conductivity which is the major contribution for the reflection of the electromagnetic radiation[5]. The current shielding metals which achieve an excellent shielding effectiveness (SE) such as silver, nickel, copper, gold and their coating are suffering from their high density and high cost. Ni-Fe alloy and permalloy are attractive because they have both good electrical conductivity and magnetic permeability, thus providing reflection and absorption losses at the same time. But they are only used to low-frequency magnetic shielding, and restricted by their heavy weight. The existing polymer composite shielding materials are light, but cannot be used as structural materials. Therefore light-weight shielding materials are reguired urgently, especially in the portable electronics and aerospace industries[6-8].

It is well known that magnesium is the lightest structural metallic material with attractive electromagnetic shielding properties at ambient temperature, which are considered to be the very potential EMI shielding materials[9]. The WE (Mg-Y-Nd) series have become relatively successful magnesium alloys with superior mechanical properties at high temperature and good corrosion resistance, and already been applied in the aerospace area[10-14]. In the present study, the effects of Nd content on the microstructure, the mechanical properties and EMI shielding properties of as-cast Mg-Y-Zr-Nd alloys were investigated. In addition, the alloy with good combination of mechanical and shielding properties was heat treated in order to attain better shielding effectiveness.

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1 Experiment

Four alloy ingots were prepared from high purity Mg (99.98%), Mg-30Y (wt%) , Mg-30Nd (wt%) and Mg-27.85Zr (wt%) master alloy by melting in an electrical resistance furnace in a mild steel crucible at 750 ℃. Flux was used during this process to prevent the oxidative combustion of metal liquid surface. The additions of Nd into the four alloys were 0 wt%, 1 wt%, 3 wt% and 4 wt%, respectively. The actual chemical compositions of these alloys were determined by an inductively coupled plasma analyzer (ICP), as listed in Table 1. Two types of heat treatments were performed to the cast ingots, namely solid solution at 525 ℃ for 8 h (T4), and T4 plus artificial ageing at 150 ℃ for 24 h and then cooling in air (T6).

Specimens for microstructure observations were prepared by mechanical grinding, polishing, and subsequent etching. The specimens were etched with a mixture of 0.8 g picric acid, 10 mL ethanol, 2 mL acetic acid and 2 mL water. Microstructure was examined by an optical microscope (OM) and scanning electron microscope (SEM, TESCAN VEGA II LMU). Phase analysis was carried out with a Rigaku D/MAX-2500PC X-ray diffractometer (XRD). The average grain size and volume fraction of precipitates were counted by Image-pro-plus. Tensile samples were cut into rectangular shapes with 10 mm width, 2 mm thickness and 30 mm gauge length. Tensile testing was carried out on a CMT5105 machine at a crosshead speed of 3 mm/min at room temperature. Fracture surface was investigated in a scanning electron microscope (SEM). EMI SE (attenuation upon transmission) was measured by DR-S01 shielding effectiveness tester with its input and output connected to NA7300A network analyzer. The range of scan frequency was from 30 MHz to 1.5 GHz. The samples were in a disc form with 115 mm in diameter and 2 mm in thickness. Electrical conductivity of disc specimens in different conditions was measured with a conductivity meter (SigmascopeSMP10) at 20 ℃.

2 Results and Discussion

2.1 Microstructural characterization

The optical micrographs of as-cast alloys are shown in Fig.1. It is revealed that the grain size of the alloy decreases with increasing of Nd content. The average grain sizes were measured to be 70.1, 60.5, 45.2 and 42.9 μm for the alloys with 0 wt%, 1.01 wt%, 2.63 wt% and 3.30 wt% Nd, respectively. The content of Nd element as low as 2.63 wt% leads to a large maximum reduction of the grain size, which does not distinctively change when Nd content is higher than 2.63 wt%. The grain refinement might be attributed to that the enrichment of Y and Nd elements in the solid-liquid interface results in a greater degree of the constitutional supercooling and prevents the grains from growing up in the process of solidification[15,16]. Furthermore, when the content of Nd increases from 1.01 wt% to 2.63 wt% and 3.30 wt%, the eutectic or intermetallic phases in the vicinity of grain boundaries become more and bigger.

Table 1 Chemical composition of Mg-Y-Nd-Zr alloys (wt%)

Alloy	Y	Nd	Zr	Mg
YKN0	4.95	0	0.53	Bal.
YKN1	5.08	1.01	0.74	Bal.
YKN3	4.84	2.63	0.70	Bal.
YKN4	4.56	3.30	0.61	Bal.

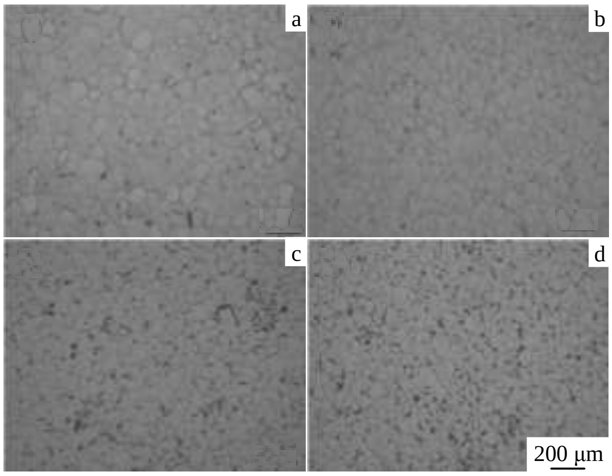

Fig.1 Optical micrographs of as-cast alloy with different Nd contents: (a) YKN0 , (b) YKN1, (c) YKN3, and (d) YKN4

The back-scattering SEM images in Fig.2 reveal that the alloys with 0 and 1.01 wt% Nd are mainly composed of α-Mg and a few cuboid-shaped phases at the grain boundaries. When Nd content increases to 2.63 wt% and 3.30 wt%, discontinuous bone-shaped phases are formed mostly in the triple junction of grain boundaries. According to the EDS results presented in Table 2, the cubic phases are mainly composed of Mg and Y, and the bone-shaped phases along grain boundaries are composed of Mg, Y and Nd.

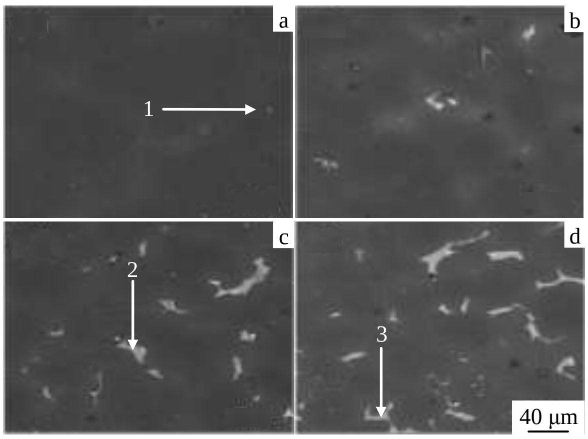

Fig.2 SEM images of as-cast alloys with different Nd contents: (a) YKN0, (b) YKN1, (c) YKN3, and (d) YKN4

Table 2　EDS results of as-cast alloys in Fig.2 (at%)

Point	Mg	Y	Nd	Zr	Phase
1	80.02	18.40	-	1.58	$Mg_{24}Y_5$
2	90.76	3.63	5.10	0.52	$Mg_{14}Nd_2Y$
3	87.78	4.21	7.58	0.42	$Mg_{14}Nd_2Y$

The X-ray diffraction patterns of as-cast alloys are shown in Fig.3. It is reveals that the quantity and the composition of the second phases change with the increase of Nd content. XRD analysis indicates that the alloy YKN0 without Nd addition contains α-Mg and a few $Mg_{24}Y_5$. With the increase of Nd addition, more $Mg_{24}Y_5$ peaks appear. The β-phase reported in the previous work [15,17] occurred when the Nd content went up to 2.63 wt%. Combining EDS and XRD results, the cuboid-shaped phase is identified as $Mg_{24}Y_5$, the discontinuous bone-shaped phase is composed of Mg, Y and Nd element, corresponding Nd:Y atom ratio is nearly 2:1. It is in agreement with the previous report that in WE54 and WE43 alloys the equilibrium β phase had a $Mg_{14}Nd_2Y$ composition[18-20].

2.2　Tensile properties

Fig.4 shows the tensile properties of the as-cast alloys at room temperature. Both ultimate tensile strength (UTS) and yield strength (YS) are enhanced with increasing of Nd content. The alloy with 2.63 wt% Nd exhibits the maximum UTS and YS, and their values are 191 and 133 MPa, respectively. The UTS is enhanced by 20 MPa and the YS is increased by 33 MPa compared with those of the alloy without Nd element. It may be because of grain refinement and precipitation strengthening [20]. While the tensile elongation drops with increasing of Nd content. The elongation is significantly decreased from 9.5% to 1.1% when the content of Nd increases from 0 wt% to 3.30 wt%. Fig.5 shows the tensile fractures of YKN0 and YKN4 alloys. It is revealed that the failure surface of YKN0 is composed of tear ridges, cleavage planes and a small amount of cavities, the grains of tear ridges have obvious traces of torn deformation, and the fracture mode of YKN0 alloy is confirmed to be as quasi-cleavage. However the deformation of the grains around tear ridges is small in the YKN4 alloy as shown in Fig.5b. The secondary cracks are observed apparently, and the YKN4 alloy thus has experienced brittle fracture, which is corresponding with its poor ductility. In a word, the Nd content of the alloy corresponding to the optimal mechanical properties should be 2.63 wt%.

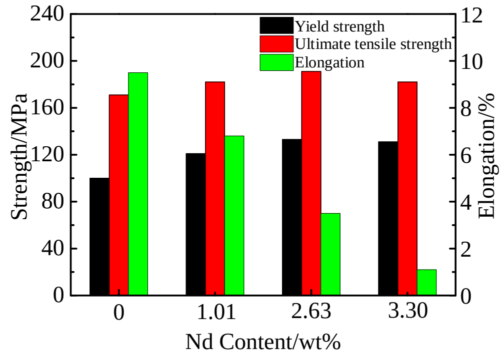

Fig.4　Room temperature tensile properties of the as-cast alloys with different Nd contents

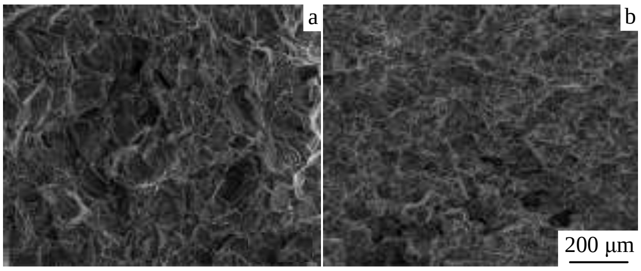

Fig.5　SEM images of tensile-ruptured surfaces of YKN0 (a) and YKN4 (b) alloys

The analysis of microstructure and mechanical properties reveals that the addition of Nd induces the obvious improvement of the strength by grain refining and the second phase precipitation. A balanced amount of fine second phases uniformly distributed on the matrix could improve the strength effectively, but excessive and coarse discontinuous networks distributed along the grain boundaries are easy to produce stress concentration and initiate the cracks during plastic straining, which deteriorate the tensile elongation.

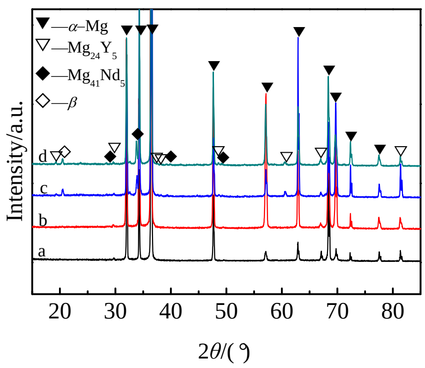

Fig.3　XRD patterns of the as-cast alloys with different Nd contents (a-YKN0, b-YKN1, c-YKN3, d-YKN4)

2.3　Electromagnetic shielding properties

The frequency dependence of EMI shielding characteristics of the as-cast alloys is illustrated in Fig.6. The as-cast alloy without Nd exhibits relatively good shielding capacity with the values varying from 70 dB to 99 dB, and the SE value is improved significantly by adding 1.01 wt% Nd content, and then increases slightly with further adding of Nd. The maximum SE is obtained in YKN3 alloy, and the value is 78~110 dB. It should be noted that four samples have excellent shielding capacity with the SE value higher than 70 dB in the frequencies varying from 30 MHz to 1.5 GHz, which exceeds the general military requirement. In usual

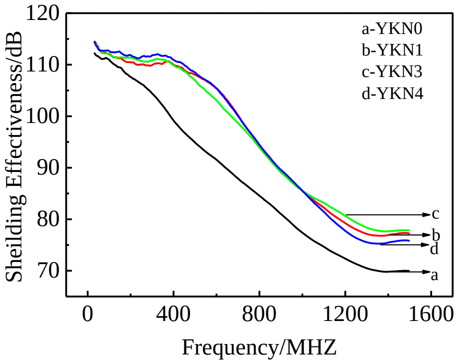

Fig.6 EMI shielding properties of the as-cast alloys vs different Nd contents

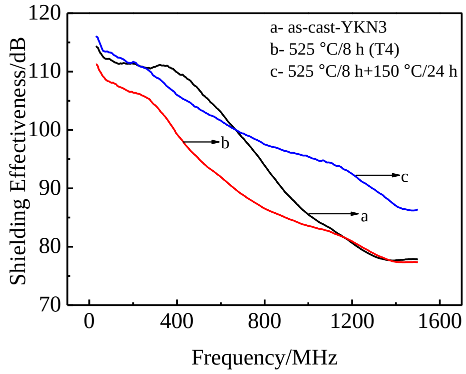

Fig.7 EMI shielding properties of the YKN3 alloy in different states

practice, SE of civil industry requirement is 30~60 dB and that of military requirement is 60~120 dB[4,5].

Table 3 shows the details of these four alloys. As observed in Table 3, the addition of Nd slightly reduces the relative electrical conductivity, significantly refines the grain size (from 70.1 μm to 45.2 μm) and increases the size and the number of phases. A large number of coarse phases enhance the scattering of electromagnetic waves, this is able to reasonably explain the fact that the SE value is significantly increased at the whole testing frequency by adding Nd element[4-7].

Solid solution at 525 ℃ for 8 h (T4), and solid solution at 525 ℃ for 8 h plus artificial aging at 150 ℃ for 24 h (T6) were performed to the YKN3 alloy. The frequency dependence of EMI shielding characteristics of the alloy in different states is illustrated in Fig.7. An obvious effect of heat treatment on EMI shielding properties is seen from this plot, and the comparison of shielding effectiveness at the frequencies of 400, 800, 1400 MHz is shown in Table 4.

After solid solution treatment, the EMI SE decreases to a large extent in the whole testing frequency range compared with as-cast sample. The solid solution treatment followed by artificial aging remarkably improves the SE, and the value is increased to 87~106 dB in the frequency range of 30~1.5 GHz. In the low frequency range the SE reaches the cast level nearly. When the frequency is greater than 800 MHz, the shielding effectiveness is much higher than the level of the cast state.

The change of the SE can be explained in terms of the variation of second phases. The coarse phases, especially the bone-shaped phases, in the triple junction of grain boundaries

Table 3 Detailed summary of the properties for as-cast alloy

Alloy	Mean grain size/μm	Area fraction of second phase/%	Relative conductivity/ %IACS	SE/dB
YKN0	70.1	0	10.78±0.06	70~99
YKN1	60.5	0.062	9.39±0.05	77~109
YKN3	45.2	1.32	8.56±0.05	78~110
YKN4	42.9	1.57	8.52±0.1	75~111

Table 4 Comparison of SE results of Mg-Y-Zr-Nd alloy in different conditions

Sample	Relative conductivity/%IACS	Shielding effectiveness/dB			SE/dB
		400 MHz	800 MHz	1400 MHz	
a	8.56±0.05	110	94	78	78~110
b	9.18±0.3	99	87	77	77~99
c	9.47±0.24	106	98	87	87~106

mostly decompose and dissolve into matrix, and the scattering loss reduces. As reported in the literature, the aging mechanism of the Mg-Y-Nd alloy at 150 ℃ is mainly based on the formation and the growth of β'', and the β'' phases with the DO19 structure is fully coherent with the matrix[12,19,21-27]. The precipitation of the second phases improves the electrical conductivity which should contribute to the reflection loss of the electromagnetic wave. At the same time, the second-phase particles distributed on the matrix increase the scattering loss of the electromagnetic wave. Therefore, the precipitation of β'' phase is beneficial to improve the shielding effectiveness and it is possible to control the electromagnetic shielding performance by different heat treatments.

3 Conclusions

1) The grain sizes of these alloys decrease with increasing of Nd content. The YKN0 and YKN1 alloys are mainly composed of α-Mg and $Mg_{24}Y_5$. With the increase of Nd addition, the compounds at grain boundaries mainly are $Mg_{24}Y_5$, $Mg_{41}Nd_5$ and β phase with a $Mg_{14}Nd_2Y$ composition.

2) The strength is enhanced with increas of Nd content. The as-cast alloy with 2.63 wt% Nd exhibits the maximum UTS and YS, and the values are 191 and 133 MPa, respectively. Compared with the alloy without Nd, the UTS and YS are enhanced by 20 MPa and 33 MPa, respectively.

3) The shielding effectiveness is significantly improved to 78~110 dB by adding 2.63wt% Nd. Solid solution treatment plus artificial ageing can further enhance the shielding effectiveness of the alloy through the precipitation of second phases.

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Mg-Y-Zr-Nd 合金微观结构、力学性能、电磁屏蔽性能研究

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摘　要：制备了不同 Nd 含量的 Mg-Y-Zr-*x*Nd 合金铸锭，研究了 Nd 含量对合金微观结构、力学性能和电磁屏蔽性能的影响。实验结果表明，当 Nd 含量增加到 2.63% (质量分数) 时，晶粒尺寸从 70.1 μm 细化到 45.2 μm，并且在晶界不连续分布骨骼状 β 相。随着 Nd 含量增加，合金强度和电磁屏蔽性能都会增加。Nd 含量为 2.63%时同时具有良好的强度和电磁屏蔽性能，T6 处理能进一步提高屏蔽效能。根据分析，以上实验结果是由于 Nd 的添加量不同引起微观结构不同造成的。

关键词：Mg-Y-Zr-Nd 合金；微观结构；力学性能；电磁屏蔽性能

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