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Effect of precipitates on mechanical and damping properties of Mg–Zn–Y–Nd alloys

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ABSTRACT

The effects of aging precipitates on microstructure, mechanical properties and damping capacities of Mg–Zn–Y–Nd alloy were investigated in this study. The structure results indicate that the as-cast alloys consist of α-Mg and W-phase when Zn/RE (rare earth element) weight ratio is about 1.7. After solution-aging treatment, the dissolved W-phase precipitates in the form of large amount of nano-scaled $MgZn_2$ and $Mg_{12}Nd$ phases. The tensile strengths of aged Mg–Zn–Y–Nd alloys are continuously enhanced with the precipitation of $MgZn_2$ and $Mg_{12}Nd$ phase particles, the highest ultimate tensile strength, yield strength and elongation reach up to 257 MPa, 152 MPa and 13.9%. The aging precipitates inhibit deformation twin from growing up and decrease its size, this favors homogeneous deformation and reduces the source of crack initiation, which results in the high elongation of aged Mg–Zn–Y–Nd alloys. The damping capacities of aged Mg–Zn–Y–Nd alloys decrease dramatically at high strain–amplitude stage compared with that of as-cast alloy. The appearance of aging twins and movement or slippage of thin twin boundaries can explain the better damping and unusual damping growth in aged Mg–3.0%–0.9%Y–0.9%Nd (wt%) alloy and Mg–4.0%Zn–1.2%Y–1.2%Nd (wt%) alloys (alloys 2 and 3). The formation of aging twin relates closely to the amount of aging precipitates, no aging twin occurs in the aged Mg–2.0%Zn–0.6%Y–0.6%Nd (wt%) alloy (alloy 1) due to lower precipitates content. The aged Mg–4.0%Zn–1.2%Y–1.2% Nd (wt%) alloy (alloy 3) with more precipitates shows lower damping values than Mg–3.0%Zn–0.9%Y–0.9%Nd (wt%) alloy (alloy 2) because of the stronger pinning effect of precipitates on dislocation.

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1. Introduction

With vibration and noise becoming serious issues in the production of modern aircraft, automobile and electronics industries, magnesium alloys are receiving considerable attention. Due to their low density, high specific strength and good damping capacity, magnesium alloys have huge potential to meet the increasing demand to eliminate undesirable vibration and noise in above areas [1–3]. Nevertheless, the majority of commercial Mg alloys have low damping capacities while the high damping Mg alloys always show poor strength, which greatly restricts their practical application [4–6]. Thus, how to balance the Mg strengthening and damping has been one of the crucial challenges for the development of anti-vibration metallic materials.

Among existing magnesium alloys, Mg–Zn–Y alloys have drawn significant interest because of their good combination of damping and strength. Usually, there are two kinds of ternary equilibrium phases in the Mg–Zn–Y system, i.e. W-phase ($Mg_3Zn_3Y_2$, cubic structure) and I-phase (Mg_3Zn_6Y, quasicrystal structure). And the traditional strengthening technologies such as plastic processing and heat treatment had been widely applied to further enhance the mechanical properties of Mg–Zn–Y alloys [7–10]. However, Wang's series studies [11,12] indicated that the thermal-extrusion processing did not balance the damping and strength well because the as-extruded Mg–Zn–Y alloy always exhibited good mechanical properties but lower damping capacities. Yan et al. reported that the solution and aging treatment improved the mechanical properties of Mg–2%Zn–1%Y–0.6%Zr (wt%) (hereafter, all compositions are in weight percents) alloy with largely sacrificing its damping capacity [13]. Furthermore, relative literature [14] on the solution-treated Mg–Zn–Y–Nd alloy revealed that the mechanical properties of the alloy got significantly enhanced, especially the elongation rises upto 20.0%. Feng et al. investigated the effect of heat treatment on the mechanical and damping properties of ZK30N alloy and found that both the tensile strength and damping capacity could get improved under ageing condition [15]. The

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above studies indicate that the aging treatment on Mg–Zn–Y–Nd alloy may give inspiration to the development of high-strength damping magnesium alloy. In spite of this, the effect of aging treatment on microstructure, mechanical properties and damping capacities of Zn–Y–Nd alloy has not yet been systematically studied, especially the influence of the variations in precipitate content of such alloy on its damping capacities is seldom mentioned.

In the present study, we applied the aging treatment to the three kinds of absolutely solutionized Mg–Zn–Y–Nd alloys with an identical Zn/RE (Y and Nd) ratio of 1.7 at same temperature of 240 °C for 20 h. The effect of precipitates on mechanical and damping properties of heat-treated Mg–Zn–Y–Nd alloy was systematically investigated.

2. Experimental details

The nominal composition of Mg–Zn–Y–Nd alloys is listed in Table 1. These alloys were prepared using high-pure magnesium, pure Zn, Mg–30%Y and Mg–30%Nd master alloys. The raw materials were melted at 760 °C under a 0.1% SF_6+CO_2-protected atmosphere. The melts were stirred and held for 25 min at 760 °C before poured into the steel-mold which had been preheated to 300 °C and then cooled in air. The ingots of alloys 1–3 were first solution treated at 520 °C for 3 h, 9 h and 12 h, respectively, then quenched in hot water at 70 °C, and the optical microstructure of all the solution-treated alloys had been examined to confirm that the second phases in the as-cast alloys had been dissolved during the solution treatment. Next, all the ingots were isothermally aged at 240 °C for 20 h.

The microstructure of the as-cast and heat-treated alloys was examined with a scanning electron microscope (SEM, JCXA-733). The phase constitutions were identified by an X-ray diffraction equipped with an X-ray diffraction (XRD, D/MAX2500PC) using Cu Kα radiation with a scanning angle from 20° to 80° and a scanning rate of 10°/min. A transmission electron microscope (TEM, JEM2000EX) operated at 200 kV was used to observe the detailed microstructures of the samples. TEM foils were prepared by jet electron polishing in ethanol alcohol at −10 °C after mechanical grinding. Tensile tests were performed on a Zwick/Roell machine with a rate of 2 mm/min at room temperature. The gauge length of the tensile specimen was 20 mm, 4 mm in width and 2 mm in thickness. Damping samples were machined to dimensions of 45 mm × 5 mm × 1 mm by an electric spark cutter. Damping capacity was measured by a dynamic mechanical analyzer (TA-DMA Q800) in single cantilever deformation mode at a measurement frequency of 1 Hz and various strains amplitudes from 6×10^{-6} to 2×10^{-3} at room temperature. The damping capacity was determined by $Q^{-1}=\tan\varphi$, where φ is the lag angle between the applied strain and the response stress.

3. Results and discussion

3.1. Microstructure

Fig. 1 shows the SEM microstructure observations of as-cast Mg–Zn–Y–Nd alloys. In all the three alloys, the microstructure of α-Mg dendrites with network eutectic phase structure distributed along grain boundary can be observed, and some granule-like particles form sporadically in the Mg matrix. With an increase in Zn and RE addition, the content of the compound phases increases and its microstructure becomes more coarsened net-like structure gradually. The grain size of Mg–Zn–Y–Nd alloy gets refined with the Zn and RE addition increasing the average size of alloy 1 is 147 µm, while those of the alloys 2 and 3 are 105 and 96 µm, respectively.

Table 1
Nominal composition of the Mg–Zn–Y–Nd alloys (wt%).

Alloy no.	Nominal composition	Zn	Y	Nd	Mg
Alloy 1	Mg–2.0%Zn–0.6%Y–0.6%Nd	2.0	0.6	0.6	Bal.
Alloy 2	Mg–3.0%Zn–0.9%Y–0.9%Nd	3.0	0.9	0.9	Bal.
Alloy 3	Mg–4.0%Zn–1.2%Y–1.2%Nd	4.0	1.2	1.2	Bal.

Fig. 2 shows the X-ray diffraction patterns of as-cast Mg–Zn–Y–Nd alloys with variations in Zn and RE content. The main phases for alloys 1–3 can be indexed as α-Mg and W-phase. No diffraction peaks corresponding to other phases can be detected within the sensitivity limit of XRD. The detail microstructure and further microanalysis of the eutectic phase formed in as-cast Mg–Zn–Y–Nd alloys are shown in Fig. 3. The high magnification back scattered electron image shown in Fig. 3a indicates that there are two kinds of eutectic phases in the as-cast alloy: the phase distributed along the grain boundaries and the granular phase in the matrix interior. The EDX results reveal that the elemental compositions of the two phases include Mg, Zn, Y and Nd. Both of the two phases are likely the W-phase because their Zn/RE atom ratios are 1.58 and 1.74, respectively, which approached 1.5. Fig. 3d shows the TEM image of the as-cast Mg–Zn–Y–Nd alloys, the intermetallic W-phase structure is observed and the corresponding selected area centered diffraction pattern exhibits the [110] zone of face centered cubic structure of W-phase with periodic arrangement. Through the analysis above, the compound phases precipitated at the grain boundary and in the matrix can be inferred to be W-phase.

Fig. 4 shows the microstructure of aged Mg–Zn–Y–Nd alloys. It reveals that most original W-phase eutectics phase formed in as-cast alloys have dissolved into the Mg matrix during the heat treatment, and there are only some residual eutectic compounds at the triple points of grain boundaries. The average grain sizes of the three aged alloys are nearly equal, about 110 µm. It can be clearly observed that innumerable fine particles distribute in the α-Mg matrix. Further confirmation of the precipitated particles in aged Mg–Zn–Y–Nd alloys follows using TEM.

Fig. 5 shows the TEM micrograph of the aged Mg–Zn–Y–Nd alloys. A dense dispersion of parallel rod-like precipitates and some lath- and sphere-shaped phases precipitated perpendicular to the end of the parallel ones can be observed in the Mg matrix. The rod-like phase is about 10 nm in width and 50 nm in length, which had been identified as $MgZn_2$ phase by Rosalie [16]. The rod-like form of $MgZn_2$ phase (referred to [0001]Mg) is typical precipitation for the aged condition in Mg–Zn based alloy. As shown in Fig. 5c, the rod-like particle can be identified as $MgZn_2$ phase under high resolution TEM, which is consistent with the earlier studies. An orientation relationship, $(2-1-10)//(0001)$, has been observed at the interface between the $MgZn_2$ phase and the matrix. Meanwhile, the relative short lath- and sphere-shaped phase, the $Mg_{12}Nd$ phase, is identified as shown in Fig. 5(c) and (d). The $Mg_{12}Nd$ is reported to have a body-centered tetragonal crystal structure with lattice parameters of $a=10.3$ Å and $c=5.9$ Å [17]. Incoherent lattice arrangements can be clearly observed along the interface between $Mg_{12}Nd$ phase and Mg matrix.

3.2. Mechanical properties

Fig. 2a displays the mechanical properties of the as-cast alloys. The result indicates that the increasing Zn and RE addition decreases continuously the ultimate tensile strength and the elongation of the investigated Mg–Zn–Y–Nd alloys. Compared with that of alloy 1, the elongation of alloys 2 and 3 exhibits a sharp decline, with a value of 13.9% and 12.5%, respectively. And the yield tensile strength seems no much sensitive to the content of Zn and RE addition. The mechanical properties of the three Mg–Zn–Y–Nd

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