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Microstructures and mechanical properties of the Mg–8Gd–4Y–Nd–Zn–3Si (wt%) alloy

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ABSTRACT

Microstructures and mechanical properties of Mg–8Gd–4Y–Nd–Zn–3Si alloy were systematically investigated using OM, SEM, XRD, TEM, hardness measurements, tensile and resonance test. The as-cast microstructure consists of α-Mg, Mg_3(GdYZn), Mg_{12}(GdY)Zn, Mg_2Si, Gd_5Si_3 and YSi_2 phases. The long period stacking ordered (LPSO) structure is found in the as-cast sample, which disappears after solution treatment. The mechanical properties of the extruded-T5 alloy are as follows: Young's modulus E=58.5 GPa, yield tensile strength $\sigma_{0.2}$=328 MPa, ultimate tensile strength σ_b=386 MPa and elongation δ=5.9%. The high Young's modulus of the alloy is attributed to the existence of Mg_2Si, Gd_5Si_3 and YSi_2 compounds with high Young's modulus. The weakening of age hardening response is ascribed to the formation of vast Gd_5Si_3 and YSi_2 compounds, which consumed plenty of rare earth atoms in the matrix and decreased the amount of β'' and β' precipitates.

1. Introduction

Magnesium alloys containing rare earth (RE) have been recognized as promising light structural materials for the racing automotive and aerospace industries due to their excellent performance at both room and elevated temperatures, especially the newly developed Mg–Gd–Y and Mg–Gd–Y–Zn system alloys [1–3]. Including, the aim of Zn addition in the Mg–Gd–Y–Zn alloys is to further improve the mechanical properties by both solid solution strengthening and age hardening [4]. However, the extensive application of these alloys has been restricted due to their low Young's modulus. In recent years, many investigators [5–7] claimed that Mg alloys containing Mg_2Si particles have high potential as a structural material since Mg_2Si exhibits a reasonably high Young's modulus of 120 GPa, low density of 1.99×10^3 kg m^{-3}, high melting point of 1085 °C, high hardness of 4.5×10^9 N m^{-2} and a low co-efficient of thermal expansion of 7.5×10^{-6} K^{-1}. Si has few solubility (0.003 at%) in solid magnesium and its addition results in the formation of the Mg_2Si intermetallic compound. Furthermore, the in-situ formation of Mg_2Si results in strong bonding between Mg_2Si and the matrix interface [8]. Traditionally, many researches have been carried out on the effect of Si addition on the microstructures, creep properties, ageing and corrosion behavior of AZ91 magnesium alloy [9–12] and corrosion behavior of Mg–Zn–Mn alloys [13–15]. To date, limited research has been done on the microstructures and mechanical properties of Mg–Gd–Y–Zn system alloys containing Si.

In our previous work [16], we found that the addition of Si (1.0 wt%) can improve the Young's modulus from 44.0 GPa to 51.0 GPa, while decrease the mechanical properties of the Mg–8Gd–4Y–Nd–Zr–Si alloy. In the present paper, our attention will be paid to the microstructures and mechanical properties of the Mg–8Gd–4Y–Nd–Zn–3Si alloy, especially its Young's modulus. The aim of this work is to produce a novel Mg–Gd–Y–Nd–Zn–Si system alloys owning good combination of much higher Young's modulus, high strength and heat resistance. It is expected that the present effort results can be significant in promoting the development of high quality Mg alloys.

2. Experimental procedures

The alloy ingots with nominal composition of Mg–8Gd–4Y–Nd–Zn–3Si (wt%) for this study were prepared by melting high purity Mg (>99.93%), high purity Zn (>99.97%), Mg–31.25%Gd (wt%), Mg–25.48%Y (wt%), Mg–30.15%Nd (wt%) master alloys and high purity Si (>99.95%) in an electrical resistance furnace under the protection of Ar atmosphere. The master alloys, pure Zn and pure Si, were added to the melt at 760 °C and stirred about 90 s at a speed of 300 rpm, then held for 20 min. Consequently, the prepared and refined melt was poured into a preheated (250 °C) permanent low carbon steel mold (Φ 55 mm × 150 mm).

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The actual chemical composition was Mg–7.95Gd–3.84Y–0.96Nd–1.04Zn–3.17Si, which was analyzed using an Inductively Coupled Plasma Atomic Emission Spectrometer (ICP-AES). After solution treated at 500 °C for 12 h, samples were quenched into hot water at about 80 °C and subsequently cut into 15 mm × 15 mm × 2 mm pieces for ageing. The ageing treatment was carried at 215 °C in an air electric resistance furnace. The ingots were extruded into bars at 450 °C with an extrusion ratio of 16:1.

Samples for microstructure observation were initially polished using different grades of polishing papers and finally polished with 0.25 μm diamond paste. Polished samples were chemically etched in a solution of 4 vol% nital. Microstructure observations were performed on the optical microscope (OM), scanning electron microscope (SEM) with an energy dispersive spectroscope (EDS) and transmission electronic microscope (TEM). Specimens for TEM were prepared with an argon ion milling technique. X-ray diffraction (XRD) studies were carried out using a Rigaku D/max 2500 diffractometer (Cu K_α radiation) with a scanning angle from 10° to 80° and a scanning speed of 2°/min. The phases were identified by using the ICDD PDF2-2004 database in the Jade 6 software. The reported grain size of the as-cast alloy was the average of ten OM images and measured by a mean linear intercept method. Hardness tests were performed on a HV-10B type Vickers microindenter with 30 N load and 30 s holding time. The reported values of hardness in this paper were the average of nine indentations. Round tensile specimens with 6 mm gauge diameter and 30 mm gauge length were machined from the ingots and extruded bars. Tensile test was carried out on a MTS universal materials test machine at a crosshead speed of 1 mm/min, and the reported values of tensile test in this paper were the average of three specimens. Round specimens with 5 mm gauge diameter and 150 mm gauge length were used to measure dynamic Young's modulus of the alloy in resonance test.

3. Results

3.1. Microstructures of the as-cast and solution treated alloys

The microstructure of the as-cast specimen is shown in Fig. 1(a). It can be seen that the networks eutectic compounds and many block particles are distributed at the grain boundaries. The average grain size of as-cast alloy is 55 μm or less. According to the SEM image (Fig. 1(b)), the network shaped phase (as shown by arrow A), gray phase (as shown by arrow B) and many block-shaped particles have been detected in the as-cast alloy. The chemical composition of the network shaped phase is Mg–7.02 at%Gd–3.46 at%Y–16.17 at%Zn according to the EDS result (Fig. 1(e)), this indicated that the stoichiometry of the network shaped phase is near Mg_3(GdYZn). The chemical composition of the gray phase is Mg–2.62 at%Gd–1.60 at%Y–4.57 at%Zn, this indicated the stoichiometry of the gray phase is near Mg_{12}(GdY)Zn according to the EDS result (Fig. 1(f)). The block-shaped particles can be divided into two types according to the colors: white (as shown by arrow C) and hoar (as shown by arrow D). The EDS results indicated that the white block-shaped particles are (RE+Si)-rich particles (Fig. 1(g)) while the hoar block-shaped particles are Mg_2Si particles (Fig. 1(h)). Fig. 2 shows the X-ray diffraction patterns of the as-cast and solution treated samples. It is evident to note that the phase constituents of the as-cast sample is mainly composed of α-Mg solid solution, Mg_3(GdYZn), Mg_{12}(GdY)Zn, Mg_2Si, Gd_5Si_3 and YSi_2 phases, which agreed fairly well with the EDS results in Fig. 1(e and f). In accordance with the OM and SEM images (Fig. 1(c and d)), the Mg_3(GdYZn) and Mg_{12}(GdY)Zn phases have dissolved into the matrix after solution treatment, while the (RE+Si)-rich and Mg_2Si particles still existed, and it is also confirmed by the XRD result (Fig. 2(b)).

In addition, it can be clearly seen that many fine lamellar structure in the as-cast sample (Fig. 1(a and b)) is tending to grow into the interior of the grains. This structure is named as the long period stacking ordered (LPSO) phase after the atomic arrangement, and its chemical composition is near Mg_{12}(GdY)Zn according to Ref. [17]. However, in contrast to the as-cast sample, the LPSO phase disappears after solution treatment (Fig. 1(c and d)), which is different from Zheng et al.'s experimental findings [17].

3.2. Microstructure of the extruded alloys

Fig. 3 presents the microstructure of the longitudinal and transverse direction of the extruded specimens. It is well known that Mg alloys have relatively lower stacking fault energy (60–78 kJ mol^{-1}) [18], DRX generally predominates in deformed Mg alloys. Grain refinement by DRX in deformed Mg alloys has been widely observed, especially at elevated temperature (above 513 K) [19]. However, it is found that dynamic recrystallization (DRX) does not occur in the alloy during hot extrusion. This is mainly attributed to the existence of Mg_2Si, Gd_5Si_3 and YSi_2 particles with high melting point, which are 1085 °C [6], 1700 °C [20] and 1520 °C [21], respectively. These high melting point particles can hinder the movement of dislocation, improve the density of dislocation in the matrix, consequently, make the alloy not recrystallize during extrusion even at 450 °C. In addition, the block-shaped particles observed in Fig. 1 are crushed and distributed along the extrusion direction.

3.3. Mechanical properties

The precipitation hardening curves of the as-cast and extruded specimens at 215 °C are shown in Fig. 4. It can be seen that the as-cast and extruded alloys both exhibit a weak age hardening response. The hardness of as-cast alloy is about 76 HV, increases slightly to the peak hardness of 82 HV after about 10 h, and then becomes constant for a longer time. Similarly, the hardness of extruded alloy gently reaches its peak hardness of 102 HV from 93 HV at the expense of 12 h. According to the results in Section 3.1, there are plenty of Gd_5Si_3 and YSi_2 particles in the alloy, which consumed most of the Gd and Y atoms in the matrix and decreased the number of nano-scale precipitates β'' and β'. Therefore, it is the formation of Gd_5Si_3 and YSi_2 particles that weakened the age hardening response of the alloy.

The tensile mechanical properties of the Mg–8Gd–4Y–Nd–Zn–3Si alloy are presented in Table 1. Apparently, Young's modulus of the alloy reaches 58.5 GPa or less, which is much higher than the Mg–Gd–Y system alloys (about 45.0 GPa). Furthermore, it can be seen that Young's modulus of the alloy keeps constant after hot extrusion and peak aged, which means that it is not sensitive to hot extrusion deformation and ageing treatment. After hot extrusion, the yield tensile strength (YTS) increases obviously from 237 MPa to 295 MPa, and the ultimate tensile strength (UTS) from 289 MPa to 358 MPa. After extruded peak aged, the YTS and UTS improve from 295 MPa and 358 MPa to 328 MPa and 386 MPa, respectively.

In addition, the dynamic Young's modulus of the extruded-T5 alloy is also measured by using resonance test according to the following formula:

$$E = 1.606K\frac{mL^3}{d^4}f^2 \text{ (Pa)}$$

where m, L and d are the mass, length and diameter of the cylinder sample, which are 5.46 g, 143.4 mm and 4.93 mm, respectively. K is equal to 1.005 and the average of detected resonant frequency f is 1139 Hz. After calculation, the dynamic Young's modulus E=57.1 GPa is close to the tensile test value.