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Improving strength and ductility of Mg–Gd–Y–Zn–Zr alloy simultaneously via extrusion, hot rolling and ageing

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ABSTRACT

An ultra-high strength and high ductility Mg-8.2Gd-3.8Y-1.0Zn-0.4Zr Mg alloy sheet was fabricated by vertical direct chill casting, extrusion, hot rolling and peak-ageing treatment. The peak-aged sheet shows tensile yield strength of 416 MPa, ultimate tensile strength of 505 MPa and superior elongation to failure of 12.8% at ambient temperature. The remarkable improvement of strength is ascribed to the fine β′ phase precipitated within the grains, grains with strong basal texture and the dispersed long period stacking ordered (LPSO) phases located at the grain boundaries.

1. Introduction

Mg and its alloys with low density, high specific strength and good damping capacity have been increasingly attracting scientific attentions due to the demand for the weight reduction of automobiles and aircrafts to lower the CO_2 emission and enhance the fuel efficiency [1,2]. Furthermore, it is reported that the additions of rare earth (RE) and Zn elements into Mg alloys can give rise to a considerable precipitation strengthening effect and formation of novel long period stacking ordered (LPSO) phase to overcome the disadvantages such as low strength and poor heat resistance [3–7] and maintain good ductility simultaneously [8–10].

In 2001, nanocrystalline $Mg_{97}Y_2Zn_1$ (at%) alloy with extraordinary high tensile yield strength (TYS) of over 600 MPa and elongation to failure of ~5% was developed by rapidly solidified powder metallurgy (RS P/M) processing [11,12], which stimulates the research interest on the development of ultra-high strength Mg alloys. In addition to the ultra-fine grain size of ~200 nm, the formation of LPSO phase also accounts for the impressive high strength of the RS P/M alloy. Recently, conventional extrusion plus hydrostatic extrusion and ageing were applied to produce Mg–12Gd–3Y–0.6Zr (wt%) alloy with ultimate tensile strength (UTS) of 510 MPa, TYS of 453 MPa and elongation to failure of 4% [6]. Interestingly, extruded and peak-aged Mg–10Gd–5.7Y–1.6Zn–0.5Zr (wt%) alloy with similar RE content and Zn addition exhibits high UTS of 542 MPa, TYS of 473 MPa and elongation of 8% [13], the ultra-high strength is attributed to the refined grain size and dense nano-sized precipitates, while LPSO phases precipitated inside grains contributes to the superior ductility due to the fact that LPSO phases inhibit twinning and activates non-basal slip in the Mg matrix [8,10]. Thus in addition to strengthening the alloy, the LPSO phases are also beneficial to ductility of Mg alloys.

In order to extend the applications of Mg alloys, development of high strength Mg alloy sheets with good ductility used as skin materials of transport and aerospace vehicles becomes necessary [14]. Li et al. [4] reported that high density of dislocations induced by extrusion and cold rolling can facilitate nucleation of precipitates during subsequent ageing treatment, then Mg–14Gd–0.5Zr (wt%) alloy sheet with high UTS of 482 MPa and TYS of 445 MPa was obtained, however, the elongation to failure is merely 2.0%. The addition of Zn into the Mg–Gd alloy may enhance the ductility. According to our previous study [15], Mg-8.2Gd-3.8Y-1.0Zn-0.4Zr alloy ingot subjected to large-strain hot rolling and peak-ageing exhibits ultra-high UTS of 517 MPa, TYS of 426 MPa and elongation to failure of 4.5%. The remarkable improvement of strength is ascribed to the dense distribution of fine precipitates inside grains, scattered precipitates at grain boundaries and bimodal grain size distributions. It is necessary to improve the ductility of the Mg–Gd–Y–Zn–Zr alloys without loss of strength

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through the microstructure control. In this study, large-strain rolling with up to 40% reduction per pass and total reduction of 92% were introduced to the extruded Mg–8.2Gd–3.8Y–1.0Zn–0.4Zr (wt%) alloy. The rolled sheets were age-treated at 200 °C to produce ultra-high strength and high ductility Mg sheets, the microstructure and mechanical properties after peak-ageing were investigated.

2. Experimental procedures

High quality Mg-8.2Gd-3.8Y-1.1Zn-0.4Zr alloy ingot with diameter of 280 mm and length of 2900 mm was fabricated successfully by vertical direct chill casting. The ingot was homogenized at 510 °C for 12 h, followed by warm water quenching, and then extruded into 3 rods of 60 mm in diameter through a mold with three holes at 420 °C with an extrusion ratio of 8:1 and an extrusion rate of 6 mm/s. The plates with the thickness of 30 mm were cut along extrusion direction from the cylindrical extruded rods. The extruded plates were preheated at 400 °C for 30 min in the resistance furnace, and mill rolls were heated to 400 °C by the resistance heater. Then the large-strain hot rolling was introduced with thickness reductions of 30–40% per pass, which resulted in rolled sheets with 4 mm in thickness. After each pass, the rolling samples were reheated to 400 °C and held for 10 min, and the sample cooled in the air after the final rolling pass. Then the 4 mm thick sheets were final rolled with a reduction of 40% at 350 °C and subjected to ageing treatment at 200 °C with ageing time from 0.25 h to 128 h and peak-aged sheet was obtained at 32 h. The final as-rolled and peak-aged samples are denoted as R and R+A samples, respectively.

The tensile specimens having a gauge length of 15 mm and cross-sectional area of $6 \times 1.2\ mm^2$ were cut from the sheet with tensile axes lying parallel to the rolling direction. The tensile tests were conducted at ambient temperature on an Instron 5569 testing machine with a cross-head speed of 1 mm/min. The microstructure of the alloy was observed by Olympus BX60M optical microscope (OM), JEOL JSM-7000F field emission scanning electron microscope (FE-SEM) equipped with an EDAX-TSL electron backscattered diffraction (EBSD) system and FEI-TECNAI G^2 F30 transmission electron microscope (TEM) operating at 200 kV.

3. Results and discussions

Fig. 1 shows the age-hardening curve of R sample aged at 200 °C. The hardness value increases slowly then rises rapidly after aged for 8 h. Peak hardness with the value of 128 HV is achieved at 32 h and then decreases gradually, which indicates the good thermal stability of the alloy sheet. Fig. 1b shows the nominal tensile stress–strain curves of R and R+A samples tested along rolling direction at room temperature. The obtained mechanical properties are summarized in Table 1. The UTS, TYS and elongation to failure of the R sample are 415 MPa, 316 MPa and 9.1%, respectively. Subsequent peak-ageing treatment enhances those values to 505 MPa, 416 MPa and 12.8%, respectively. Generally speaking, the ageing treatment improves the strength of the alloy at the expense of the ductility [4,6,14–16], while it is worthy to note that in addition to the achievement of ultra high-strength by peak-ageing treatment, the elongation to failure of the Mg–Gd–Y–Zn–Zr alloy is also unexpectedly improved by 40%. As shown in our previous study [15], the R+A sample exhibits much higher strength than other wrought Mg alloys with similar compositions. Although the TYS of R+A sample is slightly lower than that of Mg–14Gd–0.5Zr [4], the lower yield ratio and much better ductility makes R+A sheet definitely more capable for applications in automobile and aerospace industries as thin components [17].

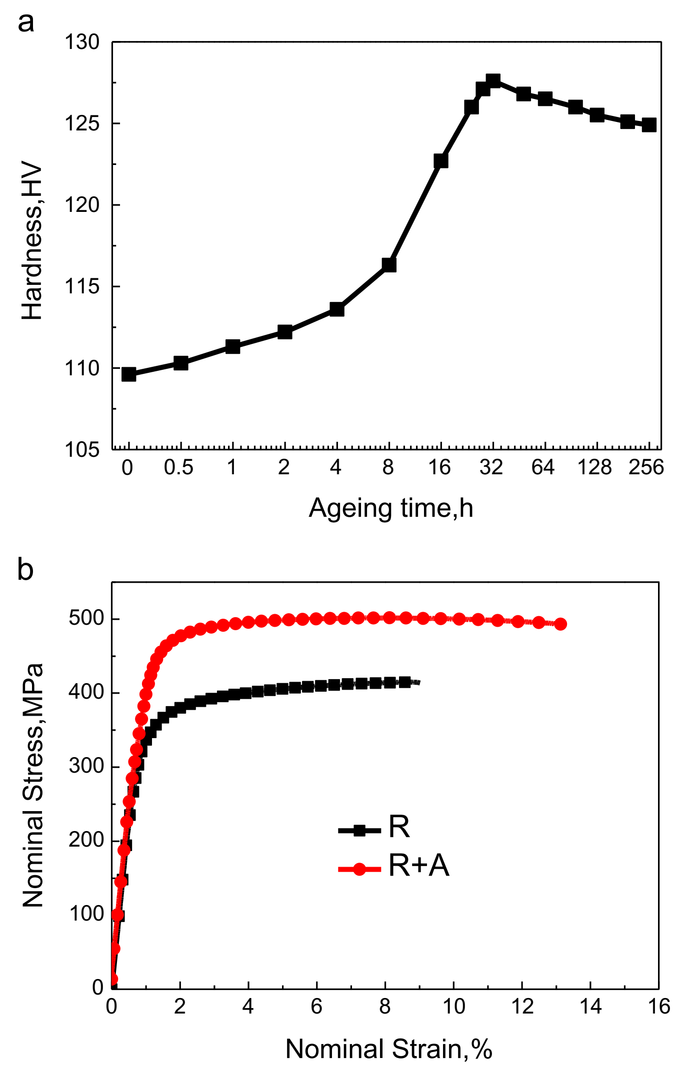

Fig. 1. (a) Age–hardening curves of the R sample and (b) nominal tensile stress–strain curves obtained from R and R+A samples.

Table 1
Tensile properties of the R and R+A samples.

Alloys	YTS (MPa)	UTS (MPa)	Elongation (%)
R	316	415	9.1
R+A	416	505	12.8

Inverse pole figures (IPFs) of the R and R+A samples shown in Fig. 2a and b reveal that homogeneous microstructure with average grain size of ~7.8 μm exhibits good thermal stability during ageing treatment at 200 °C, which agrees well with the age–hardening curves, and such fine grain size can produce significant strengthening effect according to the Hall–Petch relationship. Because the addition of RE elements can hinder dynamic recrystallization (DRX) [18], few DRXed grains can be observed and most of the grains are stretched along RD after final rolling at up to 350 °C as shown in Fig. 2a. Additionally, the color variation in the majority of grains implies that the dense dislocations and sub-grain boundaries rarely recover during ageing, which should be related to the pinning effect of fine precipitates. Fig. 2c shows the (0001), $(10\bar{1}0)$ and $(11\bar{2}0)$ pole figures of the R+A sample. The sheet has a typical basal rolling texture with a peak texture intensity of 5.4 and basal poles distribute broadly towards RD and