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Effect of aging precipitation on mechanical anisotropy of an extruded Mg–Y–Nd alloy

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ABSTRACT

Wrought Mg alloys especially precipitation-hardenable rare-earth alloys have promising potential for structural applications. However, wrought Mg alloys usually possess deformation texture leading to strong mechanical anisotropy. This is an obstacle to the application of wrought Mg alloys. Therefore, exploiting the methods to eliminate or reduce the mechanical anisotropy is one of the hot research topics related to Mg alloys. In this study, the effect of aging precipitation on the mechanical anisotropy of an extruded Mg–Y–Nd alloy was studied. The results showed that the extruded alloy presented a weak basal fiber texture and after peak-aging at 210 °C for 59 h, β' precipitates were primarily formed. The extruded alloy exhibited obvious anisotropies of yield strength and strain hardening. But after precipitation of β' precipitates the yield strength anisotropy of the peak-aged alloy was effectively reduced. The difference of yield strength between the specimens compressed along extrusion direction (ED) and perpendicular to ED was reduced from ~34 MPa to ~7 MPa. Additionally, the strain hardening rate anisotropy was also reduced by aging precipitation. Extension twinning was not largely observed in the deformed samples indicating it is not the main reason contributed to the mechanical anisotropy. This study suggests that the mechanical anisotropy of wrought precipitation-hardenable Mg alloys can be effectively reduced by aging treatments.

1. Introduction

Mg alloys have attracted extensive research attention in recent decade and gained increasing applications in transportation industries. However, at present most of the Mg alloys used for auto parts are limited to die castings, and the cast alloys generally suffered from poor mechanical properties [1]. Compared to the cast alloys, wrought Mg alloys possess higher mechanical strength and diverse properties and are expected to gain more range of applications [2]. However, as an hcp structure, Mg alloys tend to form strong texture during processing. For example, strong {0001} basal texture was usually formed during rolling [2–4] and fiber texture during extrusion [1,5]. This largely reduces the workability of Mg alloys being one of the major problems hindering their widespread applications [1]. Moreover, wrought Mg alloys with strong texture normally exhibit strong mechanical anisotropy which is detrimental for structural application [1,2]. Therefore, it is crucial to investigate the effect of texture on mechanical anisotropy of Mg alloys.

In previous study, the effects of grain orientation on microstructure development and mechanical properties have been extensively studied. It was found that texture has significant influence on mechanical properties and $\{10\bar{1}2\}$ extension twinning generally played a major role in the mechanical anisotropy and tension–compression asymmetry of Mg alloys [6,7]. However, most of the examined Mg alloys in previous studies are AZ alloys [5–7]. The effects of grain orientation on the mechanical properties of high strength Mg alloys have seldom been reported.

Mg–Y–Nd alloy is one of high strength rare earth Mg alloys, which has gained successful application in aerospace and racing automotive industries. It is well known that the high strength of the alloy is achieved mainly by precipitation hardening. At present the characteristics of the precipitates and hardening response of Mg–Y–Nd alloys have been well understood [8–10]. It is known the β' precipitate particles formed at 210 °C can effectively harden the Mg–Y–Nd alloys [11,12]. However, to date what the effect of the precipitates on work hardening and mechanical anisotropy is not known. To the authors' best knowledge, even the texture of extruded Mg–Y–Nd alloys and the effect of texture on mechanical anisotropy have not been reported.

Considering Mg alloys likely form texture during processing and aging precipitation is needed for strengthening rare-earth Mg alloys, knowledge on the effect of precipitates on mechanical anisotropy is desirable. Therefore, in this study an extruded Mg–Y–Nd alloy (Mg–5.5%Y–2.7Nd–0.04%Zr) was produced. The texture

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of the as-extruded alloy was examined and its effect on mechanical anisotropy was examined. Moreover, the extruded alloy was aged and the effect of the precipitate particles on mechanical anisotropy was investigated.

2. Experimental procedures

The starting material was an extrusion billet with the nominal composition of Mg, 5.52 wt.%Y, 2.69 wt.%Nd, 0.04 wt.%Zr and 0.17 wt.%Ni. It was in the form of a cylinder with the dimensions of 85 mm × 200 mm. Cylinders were cut from the as-received Mg–Y–Nd alloy and solution treated at 525 °C for 24 h and then hot-extruded into rods with a diameter of 16 mm. The extrusion ratio was about 28:1. The temperature of the ingots was kept at 450 °C during the whole extrusion process. Cylindrical specimens (Φ8 mm × H10 mm) were machined from the extruded alloy for compression test. Half of the specimens were aged at 210 °C for 59 h to induce precipitate particles.

Compression tests were conducted at room temperature on a Gleeble-1500D test machine at a strain rate of $0.01\ \mathrm{s}^{-1}$. To examine the mechanical anisotropy, specimens were compressed with compression direction (CD) either parallel to ED or perpendicular to ED and referred to as CD//ED specimens and CD⊥ED specimens, respectively in the follows. For either type of test, three samples were used and considerably repeatable results were obtained. The texture of the extruded alloy was examined by X-ray diffractometer (XRD, Rigaku D/Max 2500) with CuKα radiation, a voltage of 40 kV and a current of 100 mA. The microstructure of the alloys was examined by optical microscope and electron backscatter diffraction (EBSD) analysis using a HKL Chanel 5 System (Oxford system equipped in a FEI Nova 400 FEG-SEM). The mean grain size of the alloy was determined by linear intercept method based on optical micrographs. The precipitates in the aged alloys were characterized by transmission electron microscopy (TEM, ZEISS Libra200FE) with accelerating voltage of 200 kV. The specimens for TEM examination were ground with SiC paper by hand and the final thinning of the specimens was executed by a precision ion polishing system (GATAN 691).

3. Results

Fig. 1a shows the microstructure of the extruded Mg–Y–Nd alloy. It is seen that the extruded alloy contains fine and equiaxed grains with an average grain size of approx. 20–25 μm. A few randomly distributed particles were also observed, which contain a large amount of yttrium and was formed during solidification and hardly dissolved into matrix during solution and aging treatments. Fig. 1b presents the XRD pole figure of the extruded Mg–Y–Nd alloy. It indicated that $\{0001\}$ fiber texture was formed during extrusion which is similar to AZ Mg alloys, but the intensity of the fiber texture is much weaker, about 2.2 multiple times of random, compared to that formed in AZ Mg alloys. This result is in agreement with the previous findings that Mg alloys containing additions of yttrium and rare earth elements such as neodymium can develop more random textures during hot process [13,14]. Moreover, another relatively weak texture component with $\langle 0001 \rangle$ parallel to the ED was also observed. The presence of this unexpected texture component in extruded Mg alloys was previously reported by Twier et al. in extruded magnesium–yttrium–gadolinium alloy Elektron 675 [15]. It was thought this texture was developed by preferential grain growth but the complete mechanism has not been understood.

The aging precipitation in the Mg–Y–Nd alloy at different temperatures has been examined by XRD and TEM in a previous study [12]. Here, Fig. 2a shows the TEM micrograph of the Mg–Y–Nd alloy after peak aged at 210 °C for 59 h and the corresponding electron diffraction pattern is shown in Fig. 2b. The large bright diffraction spots in the diffraction pattern are from the Mg matrix and the extra weaker diffraction spots at $1/2\{1\bar{1}00\}_{\mathrm{Mg}}$ in the pattern were indexed to the β' precipitates formed during aging. It should be mentioned that although the main precipitate phase was of β' under this treatment condition, β'' and β precipitates in small amount were also detected by XRD examination in our previous study [12]. It is known that the β' precipitates are semi-coherent with the matrix and are considered as the most effective phase for age strengthening in Mg–Y–Nd alloys [11]. Previous studies revealed that β' precipitate has an orthorhombic (mmm) crystal structure with the lattice parameters of $a = 0.640$ nm, $b = 2.223$ nm and $c = 0.521$ nm [16]. Also, it was generally accepted that the β' phase in WE54 alloy has the composition of $\mathrm{Mg_{12}NdY}$, though $\mathrm{Mg_{24}Y_2Nd_3}$ composition was also reported in WE43 alloy [8,11,16]. From the diffraction pattern shown in Fig. 3b, it was also revealed that the orientation relationship between the β' precipitate and the matrix is $\{0001\}_{\mathrm{Mg}}//\{001\}_{\beta'}$, $\{1\bar{1}00\}_{\mathrm{Mg}}//\{010\}_{\beta'}$. This orientation relationship is in agreement with the majority of previous reports on magnesium-rare earth alloys [8,16].

To evaluate the mechanical anisotropy of the Mg–Y–Nd alloys, the extruded and peak-aged alloys were compressed along the ED, referred to as CD//ED specimens or perpendicular to the ED, referred to as the CD⊥ED specimens. Fig. 3 presents the true stress–true strain curves of the four compression specimens. It is clear that the peak-aged alloys exhibits higher yield strength than the extruded alloys due to the precipitation strengthening. For both the extruded and peak-aged alloys, the CD//ED specimens present higher yield strength than the CD⊥ED specimens. This yield strength anisotropy is attributed to the $\{0001\}$ fiber texture formed in the Mg–Y–Nd alloy. Moreover, it is seen that the yield anisotropy

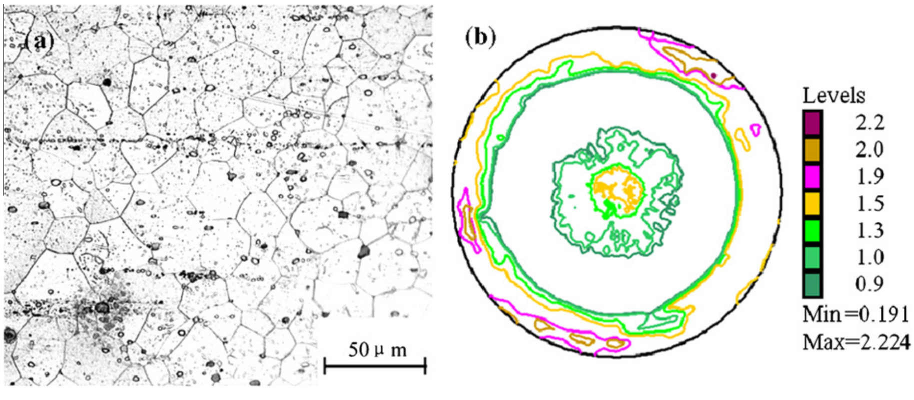

Fig. 1. (a) Optical micrograph and (b) $\{0002\}$ pole figure of the as-extruded Mg–Y–Nd alloy.