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Annealing-induced microstructural evolution and mechanical anisotropy improvement of the Mg-Gd-Y-Zr alloy processed by hot ring rolling

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ABSTRACT

Hot ring rolling (HRR) is widely used to fabricate large-size seamless ring-shape components. However, this process produces a severe mechanical anisotropy, which is not acceptable in practical industrial application and should be avoided. This paper reports the annealing-induced microstructural evolution and mechanical anisotropy improvement of HRRed Mg-8.12Gd-1.82Y-0.35Zr alloy ring. Results show that annealing treatment could improve the microstructural homogeneity of the ring owing to the occurrence of static recrystallization (SRX). SRX grains are preferentially formed at twin boundaries and initial grain boundaries due to high dislocation density, high level of stored energy, and stress concentration. Twin boundaries, to some extent, can suppress the migration of SRX grain boundaries. In addition, occurrence of SRX weakens the texture intensity and basal pole inclination, leading to a decrease in the mechanical anisotropy of the ring. Considering the weakened anisotropy, comparable strength, and improved ductility, annealing + aging (T6), compared with direct aging (T5), is a more suitable heat treatment schedule for the HRRed Mg-8.12Gd-1.82Y-0.35Zr alloy ring.

1. Introduction

Magnesium alloys are the lightest metallic structural materials, which have been the subject of many researches in recent years. Considering following characteristics, such as high specific strength, high specific stiffness, and low density [1–3], magnesium alloys are ideal potential substitutes for steel or high strength aluminum alloys used in aerospace industry. However, practical application of magnesium alloys is still limited by far, due to their relatively low absolute strength and poor heat resistance, such as ZK60, AZ91, AZ31 [4–6], etc. In the past two decades, magnesium alloys containing rare earth elements, Mg–Gd–Y–Zr series alloy in particular, have aroused intense interest of scholars and engineers owing to their high absolute strength and excellent heat resistance [7–10]. Therefore, researchers are now trying to apply Mg-Gd-Y-Zr series alloy to fabricate the component of spacecraft for saving weight, like flange connection, a ring-shape component of rocket.

Ring rolling technology is widely used to fabricate large-size seamless ring-shape component with the advantages of high material utilization, low post-processing demand, and good surface quality [11]. There has been massive experimental [12–15] and theoretical [16–24] researches conducted on ring rolling. Zeng et al. [15] applied hot ring rolling (HRR) to the manufacturing of magnesium alloy ring-shape component, and successfully fabricated a large-size AZ80-Ag alloy ring. Yu et al. [13] reported a successful application of HRR to produce a Mg-Gd-Y-Zr alloy ring. However, similar to traditional rolling, intense basal texture is a typical characteristic of magnesium alloys processed by HRR, which can lead to an obvious mechanical anisotropy, as reported in [13,15], and therefore restricts the practical industrial application of HRR-processed magnesium alloy components.

Consequently, ways to weaken the mechanical anisotropy are in urgent demand. Yang et al. [25] applied asymmetric extrusion to weaken the mechanical anisotropy of AZ31 sheets. Cross rolling is also an effective way to decrease mechanical anisotropy by changing texture type, as reported by Chen et al. [26] and Ghosh et al. [27]. Agnew et al. [28] and Wang et al. [29] pointed out that the increase of deformation temperature could active more deformation modes and thus weaken basal texture, resulting in the decrease of mechanical anisotropy. Annealing, as a post-deformation treatment method, is also widely used to decrease the mechanical anisotropy of magnesium alloys by reducing texture intensity via static recrystallization (SRX) [30,31]. Among the above-mentioned three kinds of methods, the first two need to change the deformation method and parameters. However, for a specific component with a fixed manufacturing route, changing deformation method and parameters is unreasonable. Hence, post-deformation annealing treatment seems more appropriate to weaken the mechanical

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Table 1
Chemical composition of the material used in this study (wt%).

Element	Mg	Gd (%)	Y (%)	Zr (%)	Cu (%)	Ni (%)	Fe (%)
Composition	Balance	8.12	1.82	0.35	≤0.002	≤0.002	≤0.001

anisotropy of HRR-processed component, which is the very purpose of this work.

In the present work, the variation of microstructure, texture, and mechanical properties of an Mg-8.12Gd-1.82Y-0.35Zr alloy processed by HRR after annealing treatment were investigated, and the anisotropy-weakening effect of annealing treatment was discussed. In order to capture the details of microstructural evolution during annealing, the SRX process of a selected region of the ring was tracked using quasi-in-situ electron backscatter diffraction (EBSD) method. In addition, the mechanical properties of samples treated by direct aging (T5) and post-annealing aging (T6) were compared and analyzed.

2. Experimental Procedures

Material used in this study is a semi-continuously casted ingot (ϕ450 mm × 2000 mm), whose chemical composition is shown in Table 1. After homogenization at 510 °C for 16 h, the ingot was forged into a billet with a dimension of ϕ620 mm × 105 mm. Subsequently, the forged billet was firstly machined into a doughnut-shaped blank. Fig. 1 shows the schematically illustrates of the ring rolling process [18]. The HRR process has been explained in detail in our last publication [13] and will be only briefly described here. Prior to rolling, the blank was preheated to 500 °C and kept for 3 h. The HRR process was carried out at 500 °C on a radial-axial ring rolling mill and finished within 1 min, with a finishing temperature of 360 °C. A total thickness reduction of ~54% was achieved. The dimension of the finished product Mg-8.12Gd-1.82Y-0.35Zr ring is 920 mm in outer diameter, 770 mm in inner diameter and 100 mm in height.

Samples for study were divided into two groups. One group was directly subjected to aging treatment at 225 °C for 15 h. The other was firstly annealed at 460 °C for 1 h, followed aged at 225 °C for 15 h. The samples are named according to their heat treatment conditions, as shown in Table 2. Sampling sites of the ring are shown in Fig. 2.

Table 2
Sample designations corresponding to different sample status.

Designation	Sample status
R	Rolled
T5	Rolled + aged at 225 °C for 15 h
A	Annealed at 460 °C for 1 h
T6	Annealed at 460 °C for 1 h + aged at 225 °C for 15 h

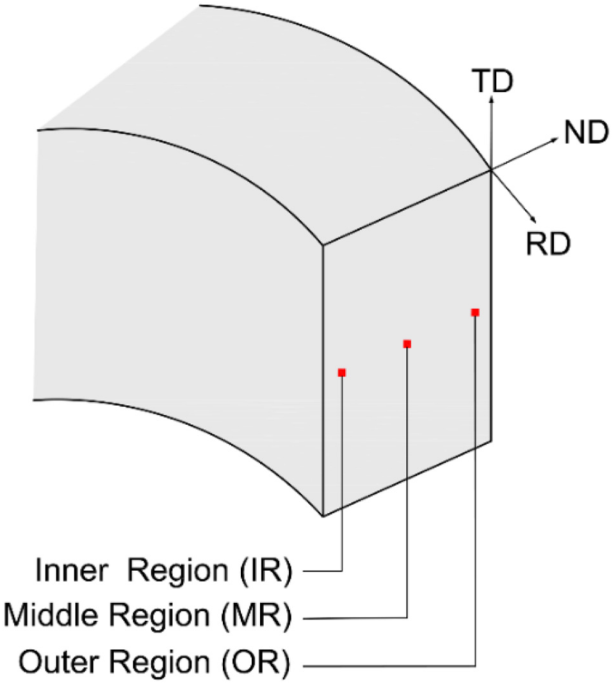

Fig. 2. Illustration of the sampling positions.

RD-TD plane was selected for microscopic observation and texture analysis. EBSD was carried out on a FEI Helios Nanolab 600i scanning electron microscope (SEM) equipped with a HKL Channel 5 software. Samples for EBSD observation were prepared through mechanical grinding and electropolishing (performed in a solution of 90% ethanol and 10% perchloric acid at a voltage of 18 V and at −35 °C for 2 min). The middle region (MR, Fig. 2) was selected to perform quasi-in-situ EBSD tracking, with the specific examination site marked by a micro-indentation. Then the quasi-in-situ EBSD scans were taken after 0 (HRRed), 3, 8, 13, 18, 23, 28, 33, 43, and 53 mins annealing treatment at 460 °C. During annealing treatment, the sample was preserved in a vacuum glass tube filled with argon to prevent oxidation. A 3-min ion milling was taken before EBSD examination to remove the oxide layer (if any). Tensile tests with loading direction parallel to rolling direction (RD, Fig. 2) and transverse direction (TD, Fig. 2) respectively were conducted at room temperature on an Instron 3369 materials tester under a constant cross-head speed of 1 mm/min. Gauge dimension of

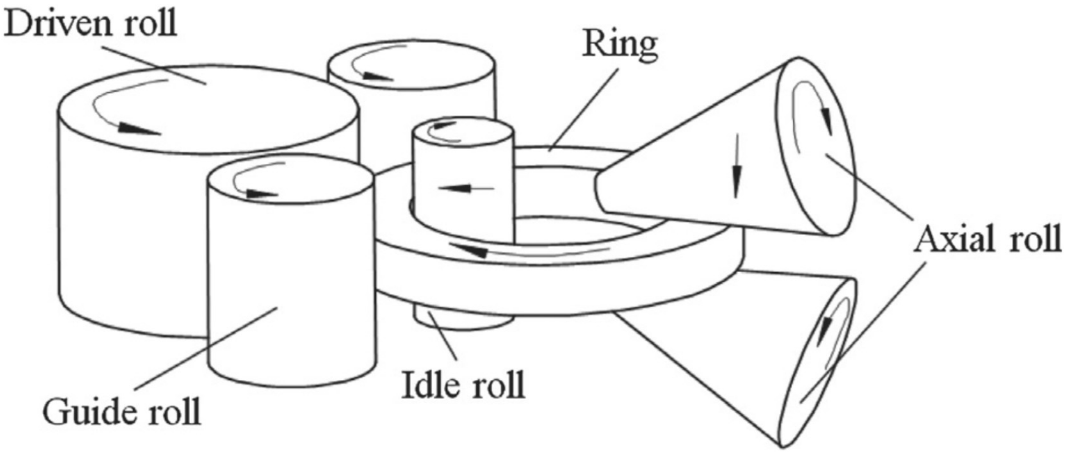

Fig. 1. Schematic diagram of the ring rolling process [18].