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Enhanced mechanical properties of a hot-extruded AZ80 Mg alloy rod by pre-treatments and post-hot compression

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ABSTRACT

A hot-extruded AZ80 Mg alloy rod was subjected to pre-treatments and post-hot compression in this work. Microstructure evolutions and resultant mechanical properties were investigated using samples with different states. The sample processed by solid solution and pre-aging (SSA) contained large-scale precipitates at the triple points of grain boundaries, while the sample processed by solid solution, pre-deformation and pre-aging (SSPDA) contained fine precipitates and different types of dislocations in the {10–12} twin interiors. Meanwhile, substructures were formed through dislocations surrounding the fine precipitates in SSPDA sample. During hot compression at 593 K, continuous dynamic recrystallization (DRX) was promoted by substructures in SSPDA sample, resulting in a full development of fine grains and a weakened texture. Inversely, discontinuous DRX happened in SSA sample, resulting in a low volume fraction of DRX grains and a relatively strong texture. The tensile testing showed that SSPDA sample had much higher strength and ductility than those of SSA sample. The enhanced mechanical properties were attributed to the completely developed DRX with grain refinement and texture weakening.

1. Introduction

Magnesium (Mg) and its alloys have many advantages such as low density, high damping capacity and good recyclability [1–3]. Among the practical Mg trademarks, AZ80 alloy with high aluminum (Al) content is especially attractive because of its high specific strength [4,5]. AZ80 alloy can be aging strengthened approaching to the high strength Mg–Gd and Mg-Er series [6–8], which is a low-cost way by free use of rare-earth elements. But taking into account comprehensive mechanical properties, the pre-aging treatment usually leads to high strength and low ductility. Like the aging treatment studied by Yu et al. [9], the ultimate tensile strength of AZ80 alloy was increased by 21% whereas the ductility was decreased by 60%. Recently, Huo et al. [10] put forward that cyclic torsion could increase the strength and decrease the tension-compression yield asymmetry of AZ80 alloy. Through cyclic torsion at different temperatures, the fatigue limit was dramatically enhanced but the ductility was destroyed. Although detwinning happened easily and delayed residual twins during fatigue cycles, detwinning had a minor effect on ductility and the serious intersections between basal dislocations and twin boundaries caused stress concentration during uniaxial loading. Wang et al. [11] combined compression with aging treatments on AZ80 alloy before uniaxial tensile testing. {10–12} twins were introduced by compression and precipitates were dispersed in the twin interiors by aging, resulting in an apparently improved strength and weakened tension-compression yield asymmetry. Nevertheless, due to the residual stress induced by the compression and aging, the ductility was still decreased compared to the as-solution samples. Thus, the previous studies on pre-deformation or pre-aging or even their combination can only bring high strength with unacceptable

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ductility.

To solve this problem in due course, one of the feasible methods may be dynamic recrystallization (DRX). Xu et al. [12] did a great deal of researches on the promotion of DRX via hot compression. The results showed that the grains can be refined effectively and good comprehensive properties can be obtained through controlling the deformation temperature and strain rate. Meanwhile, some studies showed that DRX can release residual stress and improve ductility. Huang et al. [13] rolled AZ31 alloy sheet at different final rolling temperatures and found that an extremely high temperature of 828 K can lead to completely developed DRX. The high DRX degree consumed residual stress and a good combination of tensile ductility and stretch formability was achieved. Ma et al. [14] studied the effect of number of equal channel angle pressing (ECAP) passes on the mechanical properties of a Mg-4.9Zn-1.4RE-0.7Zr alloy. The authors indicated that the DRX was gradually promoted as the pass number increasing and both the strength and ductility were improved by 32-pass ECAP. Thus, DRX can strengthen the alloy and keep the ductility, which is worthy of applying to the AZ80 alloy.

Furthermore, discontinuous precipitation usually happens when an as-solution AZ80 alloy is aging treated. These discontinuous precipitates are mainly of the β-$Mg_{17}Al_{12}$ phase, displaying parallel to the basal planes and have a coherent relationship with the matrix [15–17]. Consequently, AZ80 alloy can be aging strengthened by the discontinuous precipitates, but it fails in the poor ductility [18–20]. One way to avoid the poor ductility is adding rare-earth elements into the AZ80 alloy, forming new phases and modifying the habit planes of precipitates [21]. The second way is increasing the size of discontinuous $Mg_{17}Al_{12}$ precipitates by controlling the aging conditions. Based on the Orowan mechanism [22], if the precipitates are coarse enough and become incoherent with the matrix, dislocations will bypass the precipitates instead of cutting them. Then the shear stress is decreased and the ductility is retained. In the above two ways, the disadvantages still persist. The first way using rare-earth elements is high-cost. And the second way increasing the size of discontinuous precipitates has to sacrifice the aging strengthening effect.

The improved strength achieved by Wang et al. [11] provides a new prospect, in which the combination of pre-deformation and pre-aging was performed. The authors verified that continuous precipitation and fine precipitates were induced in the preset twin interiors. They also speculated that the incoherent relationship between the continuous precipitates and matrix contributed to the strength. However, the authors still did not clearly explain the specific structures of fine continuous precipitates inside the twins and their synergic effects on the mechanical properties. Moreover, the ductility was reduced due to the residual stress. If the reduction in ductility could be avoided by DRX during hot deformation [23], triggering continuous precipitation will have the potential to attain good comprehensive properties. Also, the effects of preset twins and continuous precipitates on the DRX mechanisms should be understood, since they can significantly affect the volume fraction of new grains and the final grain size.

In this study, aiming at an achievement of the AZ80 alloy with high strength and acceptable ductility, the pre-treatments including pre-deformation at room temperature and pre-aging at 473 K, and post-hot compression at 593 K were applied to a hot-extruded AZ80 Mg alloy rod. The resultant microstructures and mechanical properties were investigated. Meanwhile, the synergic effects of twinning and aging on the DRX mechanisms were discussed in detail.

2. Experimental procedure

A commercial hot-extruded AZ80 alloy rod with the chemical composition of Mg-8.4Al-0.5Zn-0.02Mn (in wt%) was used for the investigation. The rod was cut into cubic samples with the dimension of 10 mm in height (parallel to the extrusion direction (ED)) and 8 × 8 mm^2 in cross-section (parallel to the transverse direction (TD)). Solution treatment of the cubic samples was kept at 693 K for 15 h, then immediately quenched into water, resulting in equiaxed grains with the average grain size of ~82 μm.

The as-solution samples were divided into four groups, as listed in Table 1 and shown in Fig. 1. The first group (SS sample) was remained to serve as a comparison. The second group (SSA sample) was aged at 473 K for 20 h and then quenched into water. The third group (SSPD sample) was compressed to a true strain of 0.07 along the ED at room temperature. The strain rate was set at 1×10^{-3} s^{-1}. The fourth group (SSPDA sample) was prepared by a combination of pre-deformation and pre-aging treatments, which was performed by compression to a true strain of 0.07 (under the same condition with SSPD sample) and subsequent aging at 473 K for 20 h (under the same condition with SSA sample). Finally, the SS, SSA and SSPDA samples were pre-heated to 593 K and kept for 5 min, then hot compressed to a true strain of 1.6 at 593 K and immediately water quenching. The hot compression direction was along the ED and the strain rate was set at 3×10^{-1} s^{-1}.

The microstructures were examined by optical microscopy (OM), scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) with orientation microscopy (OIM). The samples were mechanically polished, and etched in a picral solution of 10 g picric acid, 25 mL distilled water, 25 mL acetic acid and 175 mL ethanol. For the SEM and EBSD observations, the samples were mechanically polished once again, and electropolished in a solution of nitric acid, glycerol and ethanol with a 1:3:6 vol ratio. Further internal microstructures were investigated using transmission electron microscopy (TEM). The TEM foils were prepared by ion milling method after mechanical grinding. All directions of the OM, SEM, EBSD and TEM observations in this work were along the ED (namely, the compression direction).

The uniaxial tensile tests were applied to the hot compressed samples at room temperature at an initial strain rate of 3×10^{-3} s^{-1}. The dimension of the gauge area was 5 mm in length (perpendicular to the compression direction), 1.5 mm in width and 1 mm in thickness. The yield strength (YS), ultimate tensile strength (UTS) and fracture elongation (FE) were obtained from the average values of triplicate tests for each condition.

3. Results

3.1. Microstructures developed by pre-treatments

Fig. 2 shows the microstructures of the samples at different states. Equiaxed grains with an average grain size of ~82 μm can be observed in the SS sample (Fig. 2(a)). After aging at 473 K for 20 h, as shown in Fig. 2(b), large-scale precipitates are concentrated at the triple points of the grain boundaries in SSA sample. Fig. 2(c) and (d) present the microstructures evolved by pre-deformation and subsequent aging. A large number of twins are introduced into SSPD sample and fine precipitates are diffused both inside and outside the twins in SSPDA sample. During the pre-treatments, the average

Table 1
Abbreviations for samples used in this work.

Abbreviation	State
SS	Solid solution
SSA	Solid solution and aging
SSPD	Solid solution and pre-deformation
SSPDA	Solid solution, pre-deformation and aging