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Plastic deformation and dynamic recrystallization behaviors of Mg–5Gd–4Y–0.5Zn–0.5Zr alloy

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Abstract

A newly developed magnesium alloy Mg–5Gd–4Y–0.5Zn–0.5Zr (GWZ540) was hot extruded and then compressed at temperatures between 573 and 673 K and strain rates ranging from 2×10^{-4} to $2 \times 10^{-1}\ \mathrm{s}^{-1}$. The stress–strain behaviors and volume fraction of dynamic recrystallized (DRX) grains were determined. It is shown that the form of the flow stress curves is sensitive to temperature and strain rate and DRX mechanisms of the alloy varied as deformation progresses. High density dislocation was formed at boundaries of coarse grains and around some particles of second phase at first. Dislocation cell walls then were formed and converted into subgrain boundaries. New recrystallized grains were formed finally at the base of subgrain boundaries and particles of second phase.

Keywords: Mg alloy; Mg–5Gd–4Y–0.5Zn–0.5Zr; Deformation; Dynamic recrystallization; Microstructure evolution

1. Introduction

Magnesium alloys containing rare earth elements Gd and/or Y such as Mg–6Gd–1Zn, Mg–12Gd–1Zn, Mg–12Gd–4Y–1Zn, Mg–10Gd–2Y–0.5Zr and Mg–10Gd–5Y–0.5Mn have been developed and extensively investigated recently [1–6]. Comparing with commercial magnesium alloys including WE54 the Mg–Gd–Y system alloys have higher specific strength at both room and elevated temperatures and good creep resistance. However, the Mg–Gd–Y alloys have limited ductility, especially at room temperature. During thermomechanical processing, control of microstructure evolved by dynamic recrystallization (DRX) is one of the most important factors to improve the ductility of Mg alloys. In hcp structure materials with high stacking fault energies such as magnesium alloy materials, the characteristic flow behaviors and the associated new grains evolved by dynamic recrystallization have been studied experimentally and theoretically [7–11]. It was found that the mechanisms of DRX depended on the deformation mechanisms, which changed with temperature. Low-temperature DRX (LTDRX) below 473 K was associated with the operation of twinning, basal slip and (a + c) dislocation glide. The intermediate DRX was associated with extensive cross-slip. At temperatures ranging from 573 to 723 K both bulging of original grain boundaries and subgrain growth were the operating DRX mechanisms. Up to now, almost all research published on deformation and dynamic recrystallization behaviors in magnesium alloys were concentrated on Mg–Al–Zn system and Mg–Zn–Zr system (such as AZ31 and ZK60). However these magnesium alloy systems are generally unsuitable for use above 523 K. The works on deformation behaviors of Mg–Gd–Y alloys and recrystallization mechanisms of these Mg alloys are quite limited and unclear, as far as the authors know. The present work will pay attention to hot compression deformation and the accompanied dynamic recrystallization behaviors of precipitation strengthened magnesium alloy Mg–5Gd–4Y–0.5Zn–0.5Zr which exhibits higher tensile strength and larger elongation than WE54 [12]. The relationship between flow behavior and the evolution process of DRX new grain structures of the alloy is discussed in the paper.

2. Experimental procedures

The test alloy Mg–4.8Gd–3.7Y–0.5Zn–0.5Zr (wt.%) (GWZ540) was prepared using pure metals of Mg, Zn and Y with high purity (99.9 wt.%) and master alloys Mg–30.6Gd and Mg–30.33Zr (wt.%) in a mild steel crucible under protection

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of a mixed atmosphere of SF_6 (10 vol.%) and CO_2 (bal.). The chemical composition of the alloy was analyzed by inductively coupled plasma analyzer (ICP-GENESIS). The ingots 45 mm in diameter were homogenized at 793 K for 10 h followed by quenching into water at 333 K, and then they were hot extruded at 523 K with an extrusion ratio of 16 into rods 12 mm in diameter. After being machined into diameter 10 mm and length 15 mm, the samples were hot compressed using an electro-hydraulic servo materials testing machine (Zwick-10 kN) at temperatures of 573, 623 and 673 K at strain rates of 0.02–0.0002 s^{-1}. Specimens for optical microscopy (Neophot30) observation were prepared by standard techniques and were etched using solution of 4% HNO_3 with ethanol. Thin foils for TEM were prepared by argon ion-beam thinning operation with an incidence angle of 15° and were examined in a high resolution TEM (JSM2010) with an attached Link INCA EDX system. Each flow stress–strain value is the average of three compression test results.

3. Results and discussion

3.1. Flow stress behavior

Flow curves of the alloy GWZ540 at different strain rates and at different deformation temperatures are shown in Fig. 1. Typically, the flow stress increases to a maximum and then decreases to finally attain a steady state. Such flow behavior is characteristic for hot working accompanied by DRX [13,14]. Moreover the peak stress increases with enhancing strain rate. In more detail, specific differences in the shape of the curves are evident. At 573 K the flow curve exhibits high peak stress, insignificant work softening after the peak stress and the sample breaks quickly. At 623 K the peak stress is still high but work softening is more pronounced. At 673 K steady state is attained after small peak stress with little softening. Fig. 1 suggests that it is difficult to deform the alloy at or lower than 573 K.

In general, heat activity exists during thermomechanical deformation. Arrhenius equation is widely used to describe the relation between strain rate ($\dot{\varepsilon}$), flow stress (σ), and temperature (T) at high temperatures [15]. The temperature dependence of the peak stress (σ_p) and the steady-state flow stress (σ_S) is very similar [9]. Owing to the similar behavior of σ_p and σ_S consideration will be confined to σ_p and σ_S in the following.

$$A \sinh(\alpha\sigma_p)^n = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) \tag{1}$$

where A (s^{-1}), α (MPa^{-1}) and n are materials constants; Q is the effective activation energy of deformation (kJ/mol); R is the gas constant; $\dot{\varepsilon}$ is the strain rate (s^{-1}); T is the deformation temperature in Kelvin. Eq. (1) can be written as:

$$\ln \sinh(\alpha\sigma_p) = -\frac{1}{n}\ln A + \frac{1}{n}\ln \dot{\varepsilon} + \frac{Q}{nRT} \tag{2}$$

In order to calculate A, α, n and Q, a value of α must be given in advance. The residual sum of square should be a function of α. The value of α was 0.01 MPa^{-1} when the minimum residual sum of square appeared. After the value of α was determined the values of A, n and Q were determined from Fig. 2a and b as: $A = 5.28 \times 10^{14}\ s^{-1}$, $n = 1.66$. When $\dot{\varepsilon} = 0.0002$, 0.002, 0.02 and $Q = 225{,}679$, 216,296, 208,496 J/mol, respectively, the average of Q is 216,824 J/mol, which was little smaller than activation energies of 238 KJ/mol of Mg–2.8%Ce–0.7%Zn–0.7%Zr (wt.%) by Kun Yu et al. [8]. Thus, Eq. (1) can be expressed as

$$\dot{\varepsilon} = 5.28 \times 10^{14} \sinh(0.01\sigma_p)^{1.66} \exp\left(-\frac{216,824}{RT}\right) \tag{3}$$

In fact, straight lines are obtained in a double log plot when $\ln \dot{\varepsilon}$ is plotted versus $\ln \sinh(\alpha\sigma_p)$ as shown in Fig. 2a and $\ln \sinh(\alpha\sigma_p)$ versus $1/T$ as shown in Fig. 2b. The classic interdependence of the peak stress, deformation temperature and strain rate can be seen, i.e. the peak stress increased with decreasing deformation temperature and increasing strain rate.

3.2. Microstructure evolution and DRX mechanism

Microstructures of the alloy GWZ540 after hot deformation at different temperatures to strain of 0.28 at strain rate of 0.002 s^{-1} are shown in Fig. 3. The original coarser grain and DRX grains can be clearly recognized. When compressed at 573 K, DRX does not occur completely (Fig. 3a). The volume fraction and size of dynamic recrystallized grains were increasing with enhancing deformation temperature at the given strain rate and strain. The new dynamic recrystallized fine grains

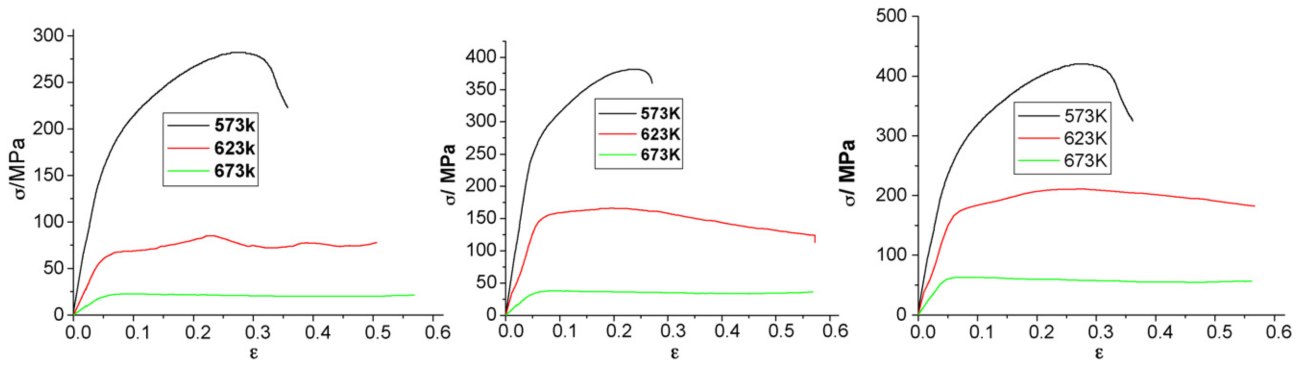

Fig. 1. True stress–strain curves of deformation of GWZ540 alloy at different temperatures and: strain rates (a) $\dot{\varepsilon} = 0.0002$ (s), (b) $\dot{\varepsilon} = 0.002$ (s), (c) $\dot{\varepsilon} = 0.02$ (s).