Materials Science and Engineering A 532 (2012) 616–622

Contents lists available at SciVerse ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

Plastic flow behavior of a high-strength magnesium alloy NZ30K

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ARTICLE INFO

Article history:
Received 7 June 2011
Received in revised form
21 September 2011
Accepted 13 November 2011
Available online 22 November 2011

Keywords:
NZ30K alloy
Mechanical properties
Constitutive relationship
Dynamic recrystallization

ABSTRACT

The plastic flow behavior of a newly developed high strength magnesium alloy, Mg–3Nd–0.2Zn–0.4Zr (NZ30K, wt.%), was investigated by tensile testing in the temperature range of 25–400 °C and a strain rate range of 1×10^{-4}–1×10^{-2}. The constitutive relationship for this alloy deformed at elevated temperatures was determined by plotting the experimental data according to the Arrhenius and hyperbolic sine models. The results show that both equations fit the experimental data reasonably well. The effect of deformation parameters on the microstructure and deformation mechanisms of the alloy was also examined using optical metallography and electron backscattered diffraction (EBSD) techniques. The results suggest that basal slip and twinning are the main deformation mechanisms at temperatures up to 200 °C; and that recrystallization occurs at deformation temperatures above 200 °C. Dynamic recrystallization (DRX) was shown to be the main softening mechanism at temperatures above 400 °C.

1. Introduction

Although magnesium alloys have lower density and significant mass saving potential compared with many structural materials, the low strength and ductility of commercially available magnesium alloys have limited their use in the transportation industry [1]. Die casting is currently the dominant manufacturing process for producing magnesium alloy components; however, the mechanical properties of magnesium die castings are low due to the gas porosity that is inherent with die castings. Recent developments that include the use of a super vacuum during die casting have significantly reduced porosity to produce higher strengths components with reasonable ductility [2]. The room temperature formability of magnesium is also low, due to its hexagonal close-packed (HCP) crystal structure. Recently, a high strength magnesium alloy, NZ30K (Mg–3Nd–0.2Zn–0.4Zr), has been developed that shows promise for use in casting and extrusion applications [3]. The new NZ30K alloy has excellent mechanical properties in the peak-aged T6 condition (6 h solution at 540 °C, water quench, and 15 h aging at 200 °C): yield strength 150 MPa; ultimate tensile strength 305 MPa and elongation 11% [4]. The NZ30K alloy was also recently exploited for extrusion applications [5].

It is important to understand the flow behavior of this newly developed alloy in order to optimize the thermal mechanical processes for making the extrusions and for understanding any secondary operations like bending or forming and also its behavior in the product. Constitutive equations best describe the mechanical response of materials at various deformation conditions; and were the subject of this report. There are two approaches to determine the constitutive relationship of magnesium alloys: the first is to describe the material behavior in terms of its microstructure, deformation conditions and various property-related materials constants [6], and the second, to describe the constitutive behavior of the material by only its deformation conditions and material constants. The first approach describes the behavior of the material based on its microstructural response, while the second approach relates the mechanical response of the material based on its stress and strain behavior at various strain rates and temperatures with the use of Eqs. (1)–(3). Eq. (1) is known as the Arrhenius relationship, while Eqs. (2) and (3) are called hyperbolic sine relationship, and both are often used to describe the constitutive behavior of different materials at elevated temperatures [7].

$$\dot{\varepsilon} = A'\sigma^{n'} \exp\left(\frac{-Q}{RT}\right) \quad (1)$$

$$\dot{\varepsilon} = A'' \exp(\beta\sigma) \exp\left(\frac{-Q}{RT}\right) \quad (2)$$

$$\dot{\varepsilon} = A(\sinh \alpha\sigma)^{n} \exp\left(\frac{-Q}{RT}\right) \quad (3)$$

where $\dot{\varepsilon}$ is the strain rate, A', A'', A, n', n, β and α are the material constants, σ is the applied stress, Q is the activation energy for deformation, R is the molar gas constant and T is the deformation temperature.

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doi:10.1016/j.msea.2011.11.034

The constitutive behavior of common wrought magnesium alloys, AZ31 [7–9], ZK60 [10] and WE54 [11], has been reported in the form of hyperbolic sine relationship, which agrees well with experimental test results. Recently two new wrought magnesium alloys, Mg–Zn–Ce alloy [12] and NZ30K [3], have been developed to provide improved mechanical properties compared with conventional AZ31 alloy, but research on their constitutive behavior is limited [13]. The aim of this work is to investigate the plastic flow behavior of NZ30K alloy prepared by direct-chill (DC) casting, in order to understand the effect of temperature and strain rate on its hot deformation behavior.

2. Experimental procedure

The NZ30K alloy was prepared using pure Mg, Zn, Mg–30Nd and Mg–30Zr master alloys in a steel crucible heated in an electrical resistance furnace under the protective gas mixture of SF_6, CO_2 and air. The alloy melt was degassed by bubbling pure Ar for about 20 min at 740 °C, following which, the slag was removed prior to casting 100 mm billets in an experimental DC casting machine. The casting speed, melt temperature and the water flow rate were controlled at 100 mm/min, 700 °C and 25 l/min, respectively.

Rectangular tensile specimens with 10 mm width, 2 mm thickness and 30 mm gauge length were machined from the center of the as-cast billets along the casting direction and tensile testing was carried out using a Zwick/Roell-20 kN machine. Before tensile testing, all specimens were subjected to a T6 heat treatment (6 h solution at 540 °C, water quench at 70 °C, 15 h aging at 200 °C, followed by furnace cooling) [4]. The tensile test temperature range was from 25 and 400 °C and strain rate from 1×10^{-4} to 1×10^{-2}. The samples were held at test temperatures for 10 min to ensure the homogeneity before testing. For each test condition, at least three specimens were tested to ensure repeatability and accuracy.

The test specimens were quenched in hot water (70 °C) immediately after fracture for microstructural analysis, preventing any microstructure changes (static recrystallization or grain growth) during slow cooling. Longitudinal samples were sectioned near the fractured surfaces, and were mounted, ground, polished and etched with a phosphoric-picral solution (0.7 ml phosphoric acid, 4.2 g picric acid and 100 ml ethanol) for optical microscopy (OM). EBSD data were collected from the polished surfaces of the flat sections parallel to the tensile direction with a TSL Hikari high speed camera fitted on a Leo 1455 Scanning Electron Microscope operated at 20 kV and with a camera working distance of 15 cm.

3. Results and discussion

3.1. Tensile test results

Fig. 1 shows the engineering stress vs. strain curves of two extreme test conditions (the highest strain rate and the lowest temperature compared to the lowest strain rate and the highest temperature). It is evident from Fig. 1 that the tensile elongation of the NZ30K alloy is remarkably enhanced with increasing deformation temperature, and it reached about 170% at 400 °C at a strain rate of 10^{-4}, suggesting that the NZ30K alloy is very amenable for secondary processing at elevated temperatures.

Since the true peak stress defines the maximum stress that can be applied to a material during deformation, which is more relevant to practical usage in industry [14]. All the engineering peak (maximum) stress is converted to the true peak stress in this work. The average true peak stress was calculated from at least three samples, and its relationship with test temperature and strain rate plotted in Figs. 2 and 3, respectively. Fig. 2 shows that the peak stress decreases with increasing deformation temperature, due to the fact

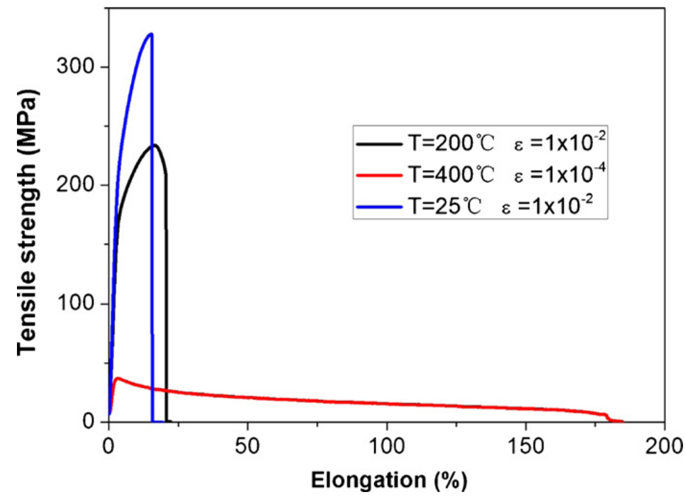

Fig. 1. Stress vs. strain curves of NZ30K alloy at two extreme deformation conditions.

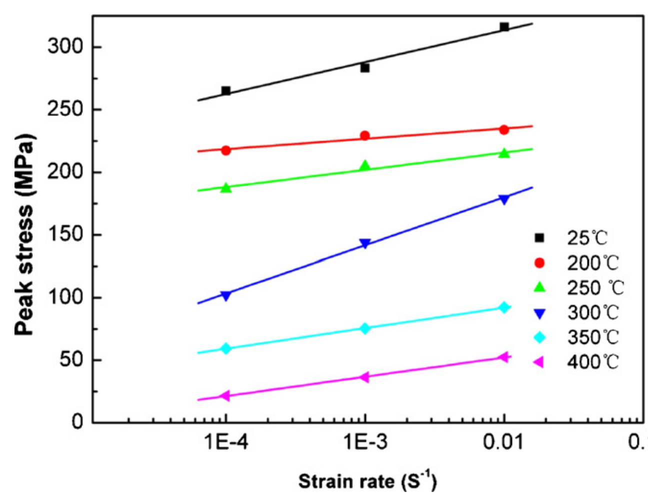

Fig. 2. Effect of strain rate on the peak stress of NZ30K alloy at various test temperatures.

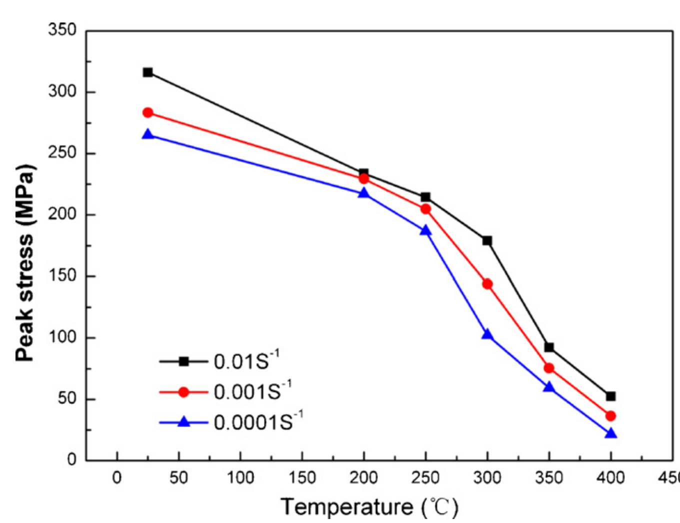

Fig. 3. Effect of temperature on the peak stress of NZ30K alloy at various strain rates.