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Modeling high-temperature tensile deformation behavior of AZ31B magnesium alloy considering strain effects

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ABSTRACT

The hot tensile deformation behaviors of AZ31B magnesium alloy are investigated over wide ranges of forming temperature and strain rate. Considering the effects of strain on material constants, a comprehensive constitutive model is applied to describe the relationships of flow stress, strain rate and forming temperature for AZ31B magnesium alloy. The results show that: (1) The effects of forming temperature and strain rate on the flow behaviors of AZ31B magnesium alloy are significant. The true stress–true strain curves exhibit a peak stress at small strains, after which the flow stress decreases until large strain, showing an obvious dynamic softening behavior. A considerable strain hardening stage with a uniform macroscopic deformation appears under the temperatures of 523 and 573 K. The strain hardening exponent (n) increases with the increase of strain rate or the decrease of forming temperature. There are not obvious strain-hardening stages when the forming temperature is relatively high, which indicates that the dynamic recrystallization (DRX) occurs under the high forming temperature, and the balance of strain hardening and DRX softening is easy to obtain. (2) The predicted stress–strain values by the established model well agree with experimental results, which confirm that the established constitutive equation can give an accurate and precise estimate of the flow stress for AZ31B magnesium alloy.

1. Introduction

Material flow behaviors during hot forming processes are often very complex [1]. The hardening and softening behaviors are both significantly affected by the deformation degree, forming temperature and strain rate [2–4]. The understandings of hot deformation behavior of metals or alloys are significant for designers working on the forming processes (hot rolling, forging and extrusion) [5,6]. The constitutive relation is often used to describe the plastic flow behaviors of metals or alloys in a form that can be used in computer code to model the deformation response of mechanical part members under the prevailing loading conditions. Therefore, some constitutive equations of materials have been developed to describe the sensitivity of the flow stress to the processing parameters under hot working. Lin and Chen [1] presented a critical review on some experimental results and constitutive descriptions for metals and alloys in recent years, and the constitutive models are divided into three categories, including the phenomenological models [6–24], physically-based models [25,26] and artificial neural network models [27–30], to introduce their developments, prediction capabilities, and application scopes. Considering the effects of strain on material constants, Lin et al. [7] proposed a revised Arrhenius type model to describe the flow behaviors of 42CrMo steel over wide ranges of strain rate and forming temperature. Also, some other investigators established the similar constitutive equations for Aermet100 steel [8], 42CrMo steel [9], 2124-T851 aluminum alloy [10], cast A356 aluminum alloy [11], commercial purity aluminum [12], T24 steel [13,14], GCr15 steel [15], considering the compensation of the strain. The modified Johnson–Cook (JC) constitutive models have been successfully established for a variety of materials within wide ranges of deformation temperature and strain rate [16,17]. Considering the coupled effects of strain, strain rate and forming temperature on the material flow behavior of Al–Zn–Mg–Cu and Al–Cu–Mg alloys, Lin et al. [18–20] proposed new phenomenological constitutive models for describing the thermo-viscoplastic behaviors of Al–Zn–Mg–Cu and Al–Cu–Mg alloys under hot working condition. In their proposed models, the material constants are presented as functions of strain rate, forming temperature and strain. The proposed constitutive model correlates well with the experimental results, confirming that the proposed model can give an accurate and precise estimate of flow stress for the Al–Zn–Mg–Cu and Al–Cu–Mg alloys investigated in this study. Gupta et al. [21] made a comparative study on the reliability of Johnson–Cook model, modified Zerilli–Armstrong model, Arrhenius type equation and artificial neural network model. Phaniraj et al. [22], Abolghasemzadeh et al. [23], and Nguyen et al. [24] studied the hot compressive deformation

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behavior of modified 9Cr–1Mo (P91) steel, bainitic and martensitic functionally graded steels, and boron steel sheets, respectively, and precise phenomenological models have been established to predict the high-temperature flow behaviors of materials. Additionally, some physically-based models have been developed. Lin et al. [25] established the flow stress constitutive equations of the work hardening-dynamical recovery period and dynamical recrystallization period for 42CrMo steel, respectively. Wang et al. [26] developed a two-stage model to determine the flow stress curves of N08028 corrosion resistant alloy at hot deformation condition, based on the dislocation density theory and kinetics of dynamic recrystallization (DRX). Meanwhile, some researchers developed the artificial neural network models to predict the hot deformation behaviors of 28CrMnMoV steel [27], 42CrMo steel [28], modified 2.25Cr–1Mo steel [29].

Due to their low density, magnesium alloys are predestined for the manufacture of automotive components, such as the paneling, covering plates, sheets, gearbox housings, and dashboards. [30,31]. Due to the hexagonal close-packed (HCP) structure, magnesium alloy has a poor plastic deformation capacity at room temperature. The uniaxial ratcheting and fatigue failure behaviors of AZ31B [32,33] and AZ91D [34] magnesium alloys under single-step and multi-step asymmetric stress-controlled cyclic loading are reported, and the stress-based fatigue life prediction models were proposed [31,32]. Despite some efforts invested into the research of magnesium alloys [30–34], the hot tensile deformation behaviors of AZ31B magnesium alloy still need to be further investigated to optimize the hot forming processing for AZ31B magnesium alloy.

The object of this study is to investigate the general nature of the effects of strain, strain rate and forming temperature on the hot tensile deformation characteristics of AZ31B magnesium alloy. Because some phenomenological models, such as Johnson–Cook (JC) constitutive model and Zerilli–Armstrong model, have some shortcomings in practical applications, and some parameters of the physically-based models are very difficult to obtain, the author chose the revised Arrhenius constitutive models considering strain effects to describe the effects of the processing parameters on the hot tensile behaviors of AZ31B magnesium alloy. The validity of the established constitutive equation is also confirmed.

2. Experiments

A commercial hot-rolled AZ31B magnesium alloy was used in this investigation, and the chemical compositions are listed in Table 1. According to the ISO 783-1999 [35], the dog-bone flat specimens with a rectangular cross section of 6 mm × 8 mm and a gauge length of 30 mm were machined along the rolled direction of the plate. The hot tensile tests were carried out on MTS-GWT2105 test machine. The displacement was measured by a grating ruler with 10 mm measuring range, and automatically recorded by computer. The accuracy of grating ruler is 0.1 μm. The hot tensile tests were carried out under five different temperatures (523, 573, 623, 673, and 723 K) and five different strain rates (0.0005, 0.001, 0.005, 0.01, and 0.05 s^{-1}). Each specimen was heated to the deformation temperature at a rate of 10 K/min, and held isothermally for 15 min prior to loading, in order to obtain the heat balance. Additionally, there are temperature fluctuations for the heating system. But, the temperature fluctuations are only 1.5 K during the whole hot tensile deformation. So, the effects of the temperature fluctuations on the hot tensile deformation behavior of material are not specially considered. The specimens were elongated until fracture, and then cooled to the room temperature in furnace. The sections of fractured specimens were polished and etched using chemical reagents. The optical microstructures in the section region were examined.

Table 1
Chemical compositions of AZ31 magnesium alloy (wt.%).

Al	Zn	Mn	Si	Cu	Ni	Be	Fe	Mg
3.19	0.81	0.334	0.02	0.05	0.001	0.02	0.005	Bal.

3. Hot tensile deformation behaviors of AZ31B magnesium alloy

3.1. True stress–strain curves and microstructural evolution

Based on the experimentally-measured loading–displacement curves, the true strain (ε), prior to necking, can be computed. i.e., $\varepsilon = \ln[(\Delta l + l_0)/l_0]$, here Δl is the amount of deformation (positive for elongation). l_0 is the initial gauge length. The typical true stress–strain curves obtained from the hot tensile experiments of hot-rolled AZ31B magnesium alloy are depicted in Fig. 1. It can be found that the effects of the forming temperature and strain rate on the flow stress are significant for all the tested conditions. The true stress–true strain curves exhibit a peak stress at small strains, after which the flow stress decreases monotonically until large strains, showing a dynamic flow softening behaviors. The deformation resistance increases with the decrease of forming temperature for a given strain rate and decreases with the decrease of strain rate for a given forming temperature. The effects of the forming temperature and strain rate on flow stress can be explained by the dynamic recrystallization and dislocation mechanisms. The deformation mechanism associated with the isothermal hot tensile test is a thermally activated process.

Also, the flow curves (Fig. 1) show a considerable strain hardening stage with the uniform macroscopic deformation under the temperatures of 523 and 573 K. Generally, the strain hardening exponent (n) is suitable to characterize the materials' uniform deformation capability, and can be evaluated as,

$$n = \frac{\partial \ln \sigma}{\partial \ln \varepsilon} \quad (1)$$

where σ is true stress, ε is true strain. Fig. 2 shows the variations of strain hardening exponent (n) with strain rate under different forming temperatures. For a given temperature, the values of n increase with the increase of strain rate. Also, Deng et al. [30] found that the sensitivity of the strain hardening exponent (n) to strain rate is more and more pronounced with the decrease of the deformation temperature. Furthermore, the values of n are relatively high under the temperatures of 523 and 573 K. Meanwhile, with the increase of forming temperature, the value of n decreases and the strain hardening stage becomes short. As shown in Fig. 1, there are not obvious strain-hardening stages when the forming temperature is higher than 623 K. It is because the dynamic recrystallization (DRX) occurs under the high temperatures, and the balance of strain hardening and DRX softening is easy to obtain. Thus, the strain corresponding to peak stress decreases (Fig. 1). Additionally, Deng et al. [30] found that, for the hot-rolled AZ31B magnesium alloy, the values of n are very low, basically negligible, under high deformation temperatures and low strain rates.

Fig. 3 shows the optical micrographs illustrating the effects of strain rate on microstructures for AZ31B magnesium alloy under 723 K. Obviously, the grain becomes fine with the decrease of strain rate. When the strain rate is decreased, the dynamic recovery rate increases and the dynamic recovery proceeds adequately. Also, the complete recrystallization occurs during hot deformation. So, the grain sizes under low strain rate are finer than those under higher strain rate.