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Modeling of flow stress for magnesium alloy during hot deformation

Yin-Jiang Qin*, Qing-Lin Pan, Yun-Bin He, Wen-Bin Li, Xiao-Yan Liu, Xi Fan

School of Materials Science and Engineering, Central South University, Changsha, 410083, China

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ABSTRACT

Based on the classical flow stress–dislocation density relation and kinetics of dynamic recrystallization (DRX), a model was developed to determine flow stress of magnesium alloy at hot deformation condition. The proposed model is capable of predicting the flow behavior of work hardening and dynamic recovery (DRV) region as well as the softening caused by DRX. To establish the model, the double-differentiation method was used to identify the critical strain for initiation of DRX, and the DRV parameter Ω was evaluated from the work-hardening behavior prior to critical strain. The net softening attributable to DRX was defined as the difference between the DRV and experimental curves, and Avrami equation was employed to represent this softening behavior. The flow stress curves of ZK60 magnesium alloy predicted by the developed model are in good agreement with experimental results, which confirms the validity of the model.

1. Introduction

Lightweight magnesium alloys have attracted significant interest in the last decade due to their potential applications for weight reduction in transportation vehicles. However, magnesium alloys have poor formability and limited ductility at room temperature ascribed to their hexagonal close-packed (hcp) crystal structure. As a result, to date, most of the magnesium products are fabricated by die casting process instead of employing plastic forming techniques such as rolling, forging, and extrusion. At elevated temperatures the workability of magnesium alloys substantially increases as additional slip systems, i.e., non-basal and $\langle c+a \rangle$ slip become sufficiently available by thermal activation [1]. Therefore, it is necessary to investigate the hot deformation behavior of magnesium alloys.

The flow behavior of metals and alloys at hot deformation condition has a great importance for designer of metal forming processes because of its effective role on the required deformation energy as well as the kinetics of metallurgical transformation such as dynamic recovery (DRV) and dynamic recrystallization (DRX). However, the flow behavior is influenced by many factors such as strain, strain rate, deformation temperature, etc. and understanding their effects is a difficult task due to their complex nature. Recently, the fast development of computing techniques led to a wide application of finite element method (FEM) simulation to study materials forming processes [2–4]. Nevertheless, numerical simulation can be truly reliable only when a proper flow stress model is available. A number of models were proposed to describe the flow stress of metals and alloys and extensive summary on different models was given in [5–7]. In the case of magnesium and its alloys, a few of previous investigations were performed to study the flow stress behavior. Frost and Ashby [8] reported that pure magnesium abided by the power law creep equation above 573 K. Galiyev et al. [9,10] found that magnesium alloy ZK60 complied with the creep equation. Based on an observation of a linear relationship between semi-log Zener-Hollomon parameter and proof stress, Takuda et al. [11,12] proposed a parametrical method to express the proof flow stress in the AZ31 and AZ91 tensile tests. Similar constitutive relationship for AZ31B magnesium alloy was determined and validated through comparison between simulated and real extrusion by Li et al. [13]. Sheng and Shivpuri [14] proposed an analytical method, which reflected temperature, strain and strain rate effect by introducing temperature-compensated strain rate, and the model was well applied on three published experimental data. Liu et al. [15] put forward a new model of flow stress characterizing DRX for magnesium alloy AZ31B.

Owing to the relative low stacking fault energy (SFE) and the lack of easily activated slip systems, DRX plays an important role during hot deformation of magnesium alloy [16]. However, almost all the flow stress models aforementioned, except the one proposed by Liu et al. in 2008 are empirical and do not take into account the effect of DRX. Since the DRX is a thermally activated process, the recrystallized volume fraction can be regarded as a function of strain through Avrami equation. Furthermore, the descending of flow stress during hot deformation is mainly dominated by the recrystallized volume fraction. Based on this idea, the dislocation model developed by Bergstrom [17,18] together with Avrami-type

* Corresponding author. Tel.: +86 0731 88830933.
E-mail address: qinyinjiang@gmail.com (Y.-J. Qin).

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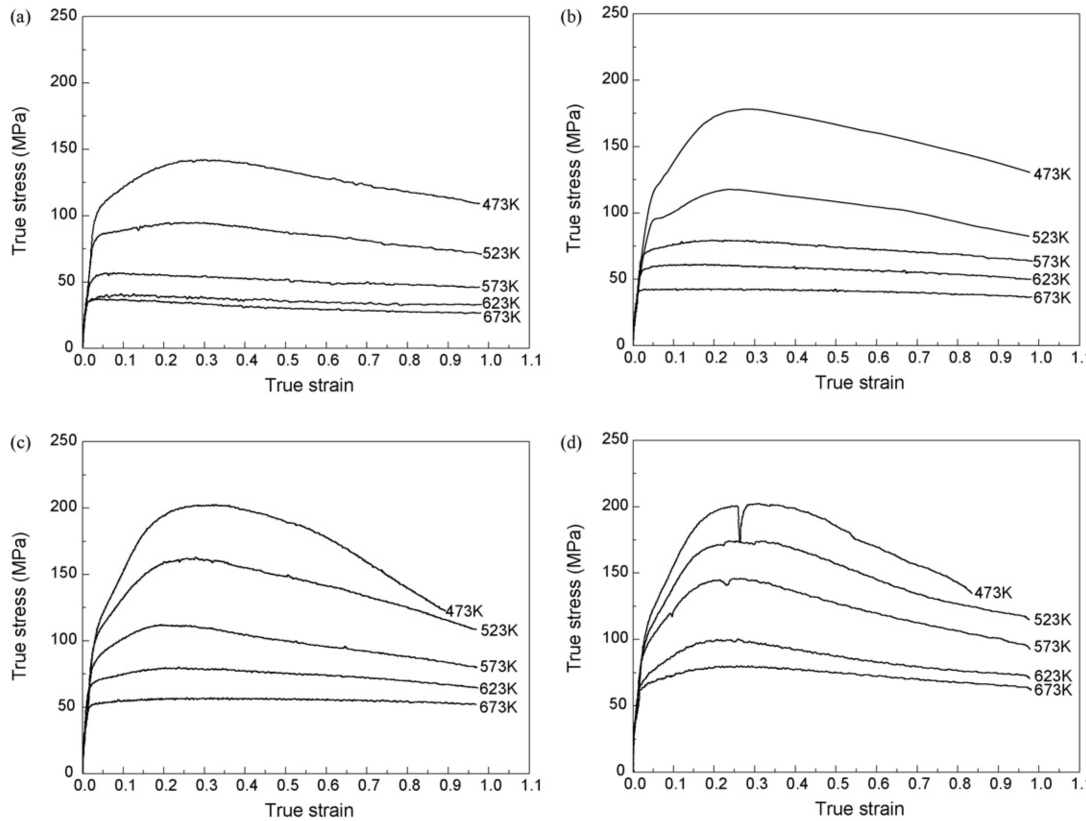

Fig. 1. True stress–strain curves for ZK60 Mg alloy at various temperatures with strain rates of (a) 0.001 s^{-1}, (b) 0.01 s^{-1}, (c) 0.1 s^{-1} and (d) 1 s^{-1}.

recrystallization kinetics equation are used to describe the flow behavior of magnesium alloy during hot deformation in this study.

2. Experiments

The material used in the present study was commercial grade magnesium alloy ZK60 (Mg–5.78%Zn–0.76%Zr). The alloy was fabricated by semi-continuous casting and homogenized at 673 K for 12 h prior to deformation. The initial grain size was about 100 μm. Cylindrical specimens with 10 mm in diameter and 15 mm in height were machined from the homogenized materials for compression tests. Uniaxial compression tests were conducted in the temperature range of 473–673 K at intervals of 50 K and constant true strain rate ranging from 0.001 to 1 s^{-1} at intervals of an order of magnitude on a Gleeble-1500 thermal simulator up to 60% of height reduction. The Gleeble compression system works with a servo-hydraulic mechanism, which deforms the sample heated electrically by its Ohmic resistance at a constant strain rate. The temperature was controlled and measured by a thermocouple welded to the sample. Graphite foils and colloidal graphite were used as lubrication between the sample and the anvils. All the specimens were heated at 10 K/s up to deformation temperatures, held 3 min to homogenize the temperature in the sample, and then deformed and water quenched. The load-stroke data recorded for every compression tests were converted into true stress–true plastic strain curves using standard equations. The true stress–true strain curves of magnesium alloy ZK60 at different strain rates are shown in Fig. 1, according to which the characteristics of flow stress curves are represented as follows:

- The overall level of flow stress curve increases with the decrease of deformation temperature and the increase of strain rate.
- In the initial stage of the deformation, hardening rate is higher than the softening rate and thus the stress increases abruptly, then the increasing rate is decreased due to the occurrence of DRV and DRX. When the hardening rate is equal to the softening rate the flow stress peak is reached.
- After the stress peak, the softening induced by DRX exceeds the hardening and the stress drops steeply. The stress becomes steady when a new balance between softening and hardening is obtained.

3. Modeling of flow stress

In the present approach, the experimental curves are considered to be the net result of the simultaneous operation of DRV and DRX in the manner typified by the schematic curves of Fig. 2. Here the uppermost curve (σ_{drv}) is regarded as resulting from the operation of DRV alone, i.e., in the absence of DRX. Although not obtainable directly from experiment, it represents the assumed work-hardening behavior of the unrecrystallization regions, e.g., in the interiors of the grains as "necklacing" proceeds inwards. This can be derived from the work-hardening behavior prior to critical strain (ε_c) for initiation of DRX, as will be demonstrated later. After the critical strain ε_c, it leads to more and more softening and is responsible for the difference between the σ_{drv} curve and DRX curve (σ_{drx}). At saturation, the value of the asymptotic stress is given by σ_{sat}. On continued straining, σ_{sat} represents the dislocation density in the most work-hardened grains therefore the driving force for the continuation of DRX.

3.1. Modeling of dynamic recovery

During deformation, the dependence of the dislocation density ρ on plastic strain ε is generally considered to be given by the