Journal of Alloys and Compounds 681 (2016) 455–470

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Modeling and application of constitutive model considering the compensation of strain during hot deformation

Yongjian Wang [a], Jian Peng [a, b, *], Liping Zhong [a], Fusheng Pan [a, b]

[a] *State Key Laboratory of Mechanical Transmission, College of Materials Science and Engineering, Chongqing University, Chongqing 400044, China*
[b] *Chongqing Academy of Science and Technology, Chongqing 401123, China*

ARTICLE INFO

Article history:
Received 14 March 2016
Received in revised form
15 April 2016
Accepted 16 April 2016
Available online 20 April 2016

Keywords:
ABAQUS user subroutine UHARD
Strain compensated arrhenius constitutive model
Hot deformation
Microstructural evolution
Homogenized 5052 alloy
Homogenized AZ31 alloy

ABSTRACT

Hot compression tests were conducted on homogenized 5052 aluminum and AZ31 magnesium alloys to establish a strain compensated Arrhenius constitutive model in the temperature range of 573–723 K and 523–673 K with strain rates of 0.001, 0.01, 0.1 and 1 s^{-1} by using a Gleeble-1500D thermo-simulator. The presented constitutive model, as well as the dynamic recrystallization (DRX) kinetics of both studied alloys, was incorporated into ABAQUS User Subroutine UHARD to provide an effective means to study hot deformation. The simulated results were subsequently referred to the cellular automaton (CA) method to simulate the microstructural evolution of the 5052 and AZ31 alloys. Results show that the constitutive model considering strain compensation offers a high accuracy. In terms of force and volume fraction of DRX, the results of the Finite Element Method (FEM) are in good agreement with the experimental results. The microstructural evolution of both homogenized 5052 and AZ31 alloys during hot compression was simulated using CA coupled the FEM results. Owing to the close connection between dislocation density and flow stress, the alloys present similar characteristics with prolonged simulation time. The mean grain sizes of both studied alloys decrease with increasing strain, revealing that a large deformation degree leads to refined grains. The mean re-grain size initially peaks and then decreases smoothly with increasing strain because of the coupled effect the nucleation and growth of re-grains.

1. Introduction

Forging, rolling and extrusion are important hot deformation processes on metals that affect the dimensional accuracy and mechanical properties of the final products. Therefore, considerable amount of research has focused on the hot deformation behavior of materials to control the forming process and consequently obtain desirable microstructure and mechanical properties. The flow behavior of materials during hot deformation is a complicated process that is significantly affected by deformation parameters, such as strain rate, deformation degree and temperature. Metallurgical phenomena, such as work hardening and softening, also depend on the given deformation condition, which directly influences the final microstructure and mechanical properties [1–4]. Therefore, modeling a constitutive equation that correlates strain, strain rate and deformation temperature is necessary to predict the flow stress and microstructural evolution during hot deformation. Meanwhile, the finite element method (FEM) has been widely used to optimize deformation parameters such as deformation temperature and strain rate. As an essential input to the FEM code, constitutive equations that contain the effects of deformation temperature and strain rate are widely cited [5–7]. However, numerical simulation results can only be credible when the precision of the constitutive equation is sufficiently high.

Driven by the significance mentioned above, researchers have conducted several hot compression tests to establish the constitutive equations in a broad range of aluminum and magnesium alloys at a given temperature. Among these models, the hyperbolic sine-typed Arrhenius model is the most widely used mainly because it considers the coupled effects of deformation temperature and strain rate [8–11]. Thus, the model provides an accurate description of the relationships among flow stress, temperature, and strain rate [12]. However, disregarding the influences of strain will lead to inaccurate understanding when evident dynamic softening appears during hot deformation. Researchers have focused on

---

* Corresponding author. State Key Laboratory of Mechanical Transmission, College of Materials Science and Engineering, Chongqing University, Chongqing 400044, China.

E-mail address: jpeng@cqu.edu.cn (F. Pan).

http://dx.doi.org/10.1016/j.jallcom.2016.04.153
0925-8388/© 2016 Elsevier B.V. All rights reserved.

improving the prediction accuracy of the strain compensated Arrhenius model in recent years [13–17].

However, the strain compensated Arrhenius model has not been widely applied to study the mechanical properties and corresponding microstructural evolution of materials, especially through FEM simulation. Therefore, the present study aims to model the hot deformation behavior of homogenized 5052 aluminum and AZ31 magnesium alloys by using a strain compensated Arrhenius model. Subsequently, the User Subroutines UHARD of the strain compensated Arrhenius model was coded into ABAQUS software to simulate hot compression. Simulated results, such as temperature field, stress field and plastic strain field, were used as input parameters to model the microstructural evolution of the alloys. Thus, the comprehensive application elucidates hot deformation and offers new methods to study this process.

2. Experimental procedures

The chemical compositions of the 5052 and AZ31 alloys are listed in Table 1. The as-cast 5052 and AZ31 alloys were homogenized at 673 K and 693 K for 12 h, respectively. The authors selected two alloys because the corresponding stress curves of the 5052 and AZ31 alloys may exhibit different hot deformation mechanisms, i.e., dynamic recovery (DRV)-dominated mechanism for the former and dynamic recrystallization (DRX)-dominated mechanism for the latter. The modeling and application of the strain compensated Arrhenius constitutive models for the two studied alloys are expected to increase the credibility of the present study.

Cylindrical specimens with a height of 12.0 mm and a diameter of 10.0 mm were machined from homogenized ingots. Isothermal compression of the homogenized 5052 and AZ31 alloys was conducted on a Gleeble-1500D thermal simulation machine in the temperature range of 573–723 K and 523 K–673 K with strain rates of 0.001, 0.01, 0.1 and 1 s^{-1}, respectively. Each specimen was heated to the deformation temperature at a rate of 10 K/s and held isothermally for 1 min before the compression test. The specimens were deformed to a true strain of 0.9 and then immediately quenched in water.

The compressed samples were cut along with the compression geometric axis. The hot compression specimens of AZ31 alloy were etched with an etchant solution of 4.2 g picric acid, 10 ml acetic acid and 70 ml alcohol. The microstructures of AZ31 alloys were obtained using an optical microscope (Zeiss Axiovert 40 Mat). The microstructures of 5052 samples were characterized by an electron backscattered diffraction (EBSD) analysis using an HKL Channel 5 system equipped with a scanning electron microscope (JEOL 7800F) operating at 20 KV.

3. Model description

3.1. FEM modeling of hot compression

In this study, the ABAQUS software was used to carry out FEM simulation of hot compression of homogenized 5052 and AZ31 alloys. According to symmetrical features of specimens, a half two-dimensional model can be used instead of a whole three-dimensional model. Fig. 1 shows the dimensions and the mesh grid of simulation model. A 4-node thermally coupled axisymmetric quardrilateral, bilinear displacement and temperature, reduction integration, hourglass control element (CAX4RT in ABAQUS) was adopted in the simulation. To export the data during the simulation process, two sets are defined in the history output of the FE model: Reference Point on the head is used to output force and displacement at each simulation increment, while P1, P2, P3, and P4 on the specimen are used to output the related equivalent strain and user-defined solution-dependent state variable.

Table 1
Chemical composition of 5052 aluminum alloy and AZ31 magnesium alloy.

Alloy	Al	Mg	Cu	Cr	Fe	Ca	Mn	Si	Zn
5052 (wt%)	Bal.	2.62	0.04	0.11	0.27	–	0.08	0.21	0.03
AZ31 (wt%)	3.20	Bal.	0.01	–	0.01	0.04	0.31	0.07	1.02

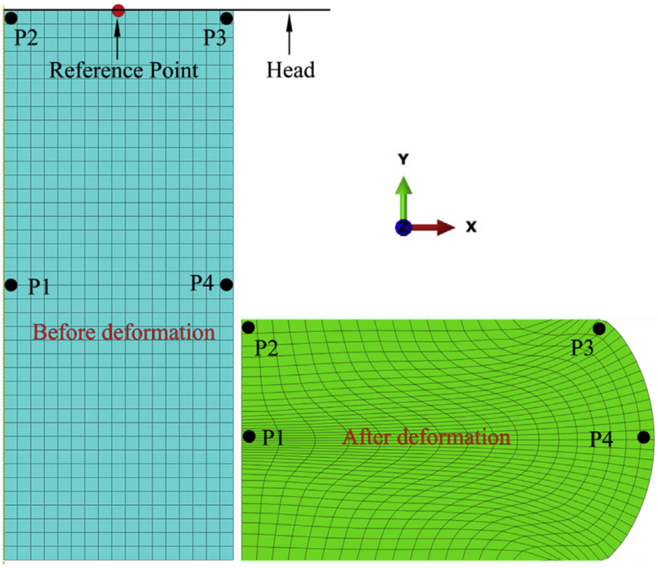

Fig. 1. FEM modeling of hot compression.

3.2. Cellular automaton

Cellular automaton (CA) is dynamic system with local interactions in which space and time are discrete. They consist of a regular lattice of cells. The state of every cell is determined by the states of neighboring cells. The adopted simulation procedure consists of three main steps. First the initial microstructure with prescribed average grain size, grain size distribution and equiaxed grain structure was generated. The experimental and numerical initial microstructure of homogenized 5052 alloy and homogenized AZ31 alloy are shown in Fig. 2. Then according to the Kocks-Mecking model [18], the flow stress can be given in:

$$\sigma = \alpha\mu b\sqrt{\rho_{mean}} \tag{1}$$

α is a constant, μ is the shear modulus, b is the Burger's vector. ρ_{mean} is the mean dislocation density, which can be expressed as:

$$\rho_{mean} = \frac{1}{N}\sum_{i,j}\rho_{i,j} \tag{2}$$

N the total number of cells in the CA model and $\rho_{i,j}$ is the dislocation density of site (i, j). The dislocation hardening and recovery are modeled by the change in the dislocation density exactly as proposed by Estrin [19]. The variation of the dislocation density of site (i, j) with respect to strain can be expressed as:

$$\frac{d\rho_{i,j}}{d\varepsilon} = k_1\sqrt{\rho_{i,j}} - k_2\rho_{i,j} \tag{3}$$

$k_1 = 2\theta_0/(\alpha\mu b)$ is a constant that represents work hardening, $k_2 = 2\theta_0/\sigma_s$ is the softening parameter that represents recovery of