Materials Science and Engineering A 534 (2012) 654–662

Contents lists available at SciVerse ScienceDirect

Materials Science and Engineering A

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

A phenomenological constitutive model for high temperature flow stress prediction of Al–Cu–Mg alloy

Y.C. Lin[a,b,*], Qi-Fei Li[a,b], Yu-Chi Xia[a,b], Lei-Ting Li[a,b]

[a] *School of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China*
[b] *State Key Laboratory of High Performance Complex Manufacturing, Central South University, Changsha 410083, China*

ARTICLE INFO

Article history:
Received 28 October 2011
Received in revised form 7 December 2011
Accepted 7 December 2011
Available online 16 December 2011

Keywords:
Metals and alloys
Constitutive modeling
Hot deformation

ABSTRACT

The high-temperature flow behavior of Al–Cu–Mg alloy is studied by the hot compressive tests over wide range of strain rate and forming temperature. Considering the negative effects of the interfacial friction on the heterogeneous deformation of specimen, the measured flow stress was corrected. The effects of processing parameters on material flow behavior are discussed. Based on the measured stress–strain data, a phenomenological constitutive model, which considers the coupled effects of strain, strain rate and forming temperature on the flow behavior of alloy, was proposed to describe the compressive behavior of the studied Al–Cu–Mg alloy. The proposed constitutive model correlates well with the experimental results, which confirms that the proposed model can give an accurate and precise estimate of flow stress for the studied Al–Cu–Mg alloy.

1. Introduction

Aluminum alloys are selected for their optimal combination of physical and mechanical properties. In particular, Al–Cu–Mg alloy is a kind of deformation aluminum alloys with high strength and low specific gravity. Due to its high strength and modulus ratio, good corrosion resistance and excellent high temperature characteristics, Al–Cu–Mg alloy is developed primarily for elevated temperature applications requiring improved short transverse properties (e.g., fracture toughness and ductility), relatively high strength, good corrosion resistance, and creep resistance at elevated temperatures. The structure and properties of the microscopic mechanism for the Al–Cu–Mg alloy is still at an exploratory stage [1–3].

Generally, the Al–Cu–Mg alloy will be subject to various hot-forming processes, such as rolling, forging, extrusion, and heat treatments. Material flow behaviors during hot formation process is often complex. The hardening and softening mechanisms are both significantly affected by the thermo-mechanical parameters, such as forming temperature, degree of deformation, and strain rate. On the one hand, a given combination of thermo-mechanical parameters yields a particular metallurgical phenomenon (microstructural evolution); on the other hand, microstructural changes in the alloys during the hot-forming process in turn affect the mechanical characteristics such as the flow stress, and hence influence the forming process [4–8]. So, understanding of the hot deformation behavior Al–Cu–Mg alloy is of great importance for designers of metal forming processes. The constitutive relation is often used to describe the plastic flow properties of alloys in a form that can be used in computer code to model the dynamic response of mechanical part members under the prevailing loading conditions. Therefore, some constitutive equations of materials were developed to describe the sensitivity of the flow stress to the strain, strain rate and forming temperatures in commercial hot working applications. Lin and Chen [9] presented a critical review on some experimental results and constitutive descriptions for metals and alloys in hot working in recent years, and the constitutive models are divided into three categories, including the phenomenological [10–24], physically based [25,26] and artificial neural network models [27–31], to introduce their developments, prediction capabilities, and application scopes, respectively. Lin et al. [10] proposed a revised Arrhenius constitutive model to describe the effects of strain on the flow behavior of 42CrMo steel over a wide range of forming temperature and strain rate. Also, some other investigators established the constitutive equations for various metals and alloys, considering the compensation of the strain [11–17]. The Johnson–Cook (JC) constitutive model [18] is a most widely known as a forming temperature, stain and strain-rate-dependent phenomenological flow stress model, and is successfully used for a variety of materials with different ranges of forming temperature and strain-rate. Samantaray et al. [19] made a comparative study on the capability of Johnson–Cook (JC), and strain-compensated Arrhenius-type constitutive models

---

[*] Corresponding author at: School of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China. Tel.: +86 015200817337; fax: +86 0731 88876504.
E-mail addresses: yclin@csu.edu.cn, linyongcheng@163.com (Y.C. Lin).

0921-5093/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2011.12.023

for representing the elevated temperature flow behavior of modified 9Cr–1Mo steel. Phaniraj et al. [21] performed constitutive analysis following the Garofalo sine-hyperbolic equation for modified 9Cr–1Mo (P91) steel over a wide range of temperature and strain rate. Mirzadeh et al. [22] derived the flow stress of a 17-4 PH stainless steel during hot compression testing by phenomenological and physically based models. Momeni and Dehghani [23,24] characterized the hot deformation behavior of 410 martensitic and 2205 austenite–ferrite stainless steel using constitutive equations and processing maps.

Despite some efforts invested into the Al–Cu–Mg alloy, its constitutive models for describing the hot compressive deformation behavior still need to be further investigated. The objective of this study is to investigate the general nature of the influence of strain, strain rate and forming temperature on the compressive deformation characteristics of Al–Cu–Mg alloy. A phenomenological constitutive model for Al–Cu–Mg alloy was developed to describe the relationship of flow stress, strain rate and temperature.

2. Experiments

A commercial Al–Cu–Mg alloy with compositions (wt.%) 4.67Cu–1.46Mg–0.63Mn–0.18Fe–0.04Zn–0.01Ti–0.12Si– (bal.)Al was used in this investigation. The orientation of the specimen cut out from the rolled Al–Cu–Mg alloy plate is shown in Fig. 1. Cylindrical specimens were machined with a diameter of 10 mm and a height of 12 mm. In order to minimize the friction between the specimen and dies during hot deformation, the flat ends of the specimen were recessed to a depth of 0.1 mm deep to entrap the lubricant of graphite mixed with machine oil. The hot compression tests were conducted on Gleeble-1500 thermo-simulation machine with the strain rate range of (0.01–1 s^{-1} and temperature range of 653–743 K. Each specimen was heated to the forming temperature at a rate of 10 K/s by thermo-coupled feedback-controlled AC current, and held for 3 min at isothermal conditions before compression, in order to obtain the heat balance. The reduction in height is 70% at the end of the compression tests.

3. Corrections of the flow stress considering negative effects of interfacial friction

Although the lubricants were used to minimize the interfacial friction between the specimen and dies, the cylinder specimen barrels out or bulges in this study. In fact, the friction, which results in the heterogeneous deformation of specimens, cannot be avoided. Furthermore, the friction effect changes with the forming temperature and deformation degree. Considering the negative effects of interfacial friction on the deformation of specimens, the measured flow stress should be corrected. The detailed procedures to correct the flow stress can be found in authors' previous publication [13].

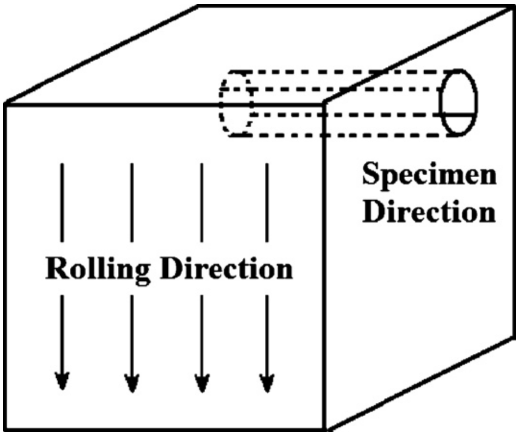

Fig. 1. Diagram showing the orientation of the specimen cut out from the rolled Al–Cu–Mg alloy plate.

Fig. 2 shows comparisons between the corrected and measured flow stress of Al–Cu–Mg alloy under tested conditions. It can be easily found that the corrected flow stresses generally are lower than the measured ones, which nicely reflects negative effects of interfacial friction on the flow stress. Also, it can be found that the effects of temperature and strain rate on the flow stress of Al–Cu–Mg alloy are significant for all the tested conditions. The flow stress increases with decreasing forming temperature and increasing strain rate. There are no obvious yield stages for all the tested conditions. The true stress–true strain curves exhibit a peak stress at a small strain, after which the flow stresses decrease monotonically until high strains, showing a dynamic flow softening. The softening phenomenon is attributed mainly to dynamic recovery and dynamic recrystallization. During initial stages of deformation there is an increase in the flow stress as dislocations interact and multiply. However, as the dislocation density rises, the driving force and rate of recovery increases. Meanwhile, the nucleation and growth of new grains occur during deformation, i.e., a microstructure of low angle boundaries and sub-grains develop. At a certain strain, the rates of work hardening and recovery reach a dynamic equilibrium. The dislocation density remains constant and steady state flow stress is obtained.

4. Constitutive modeling to predict flow stress of Al–Cu–Mg alloy

4.1. Johnson–Cook (JC) for Al–Cu–Mg alloy

Generally, the stress–strain data obtained from hot compressive tests can be used to determine the material constants of constitutive equations. Amongst the empirical and semi-empirical models, Johnson–Cook model [18] and some modified Johnson–Cook model [19,20] was successfully used for a variety of materials with different ranges of forming temperature and strain rate. The original Johnson–Cook model can be expressed as:

$$\sigma = (\sigma_0 + B\varepsilon^n)\left[1 + C\ \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right](1 - T^{*p}) \tag{1}$$

where σ is the equivalent flow stress, σ_0 is the yield stress at reference temperature and reference strain rate,ε is the equivalent plastic strain, B is the coefficient of strain hardening, n is the strain hardening exponent, C and p are the material constants which represent the coefficient of strain rate hardening and thermal softening exponent, respectively. $\dot{\varepsilon}$ is the strain rate, while $\dot{\varepsilon}_0$ is the reference strain rate, T^* is the homologous temperature, $T^* = (T - T_r)/(T_m - T_r)$. Here, T is the absolute temperature, T_m is the melting temperature (911 K for the studied Al–Cu–Mg alloy) and T_r is the reference temperature. In order to obtain the material constants of the original Johnson–Cook model, the reference temperature (T_r) and the reference strain rate ($\dot{\varepsilon}_0$) are taken as 653 K and 0.01 s^{-1}, respectively. Obviously, the lowest test temperature and strain rate are chose as the reference temperature and the reference strain rate, which can ensure the successful calculation of material constants. The yield stress (σ_0) at reference temperature and reference strain rate is measured as 108.21 MPa.

4.1.1. Determination of material constants n and B

When the strain rate is 0.01 s^{-1} and forming temperature is 653 K, Eq. (1) can be simplified as:

$$\sigma = \sigma_0 + B\varepsilon^n \tag{2}$$