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Hot deformation behavior and constitutive modeling of homogenized 6026 aluminum alloy

Liang Chen, Guoqun Zhao *, Junquan Yu

Key Laboratory for Liquid-Solid Structural Evolution and Processing of Materials (Ministry of Education), Shandong University, Jinan, Shandong 250061, PR China

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ABSTRACT

The isothermal hot compression tests of homogenized 6026 aluminum alloy under wide range of deformation temperatures (673–823 K) and strain rates (0.001–10 s^{-1}) were conducted using Gleeble-1500 thermo-simulation machine. According to the experimental obtained true stress–strain data, the constitutive equations were derived based on the original Johnson–Cook (JC) model, modified JC model, Arrhenius model and strain compensated Arrhenius model, respectively. Moreover, the prediction accuracy of these established models was evaluated by calculating the correlation coefficient (R) and average absolute relative error (AARE). The results show that the flow behavior of homogenized 6026 aluminum alloy is significantly affected by the strain rate and temperature. The original JC model is inadequate to provide good description on the flow stress at evaluated temperatures. The modified JC model and Arrhenius model greatly improve the predictability, since both of these models consider the coupled effects of deformation temperature and strain rate. However, to give more precise description, the influence of strain on the material constants should be introduced into Arrhenius model.

1. Introduction

In recent decade, the consumption of aluminum alloys experiences sustained and rapid growth worldwide due to their advantages in light-weight, high strength to weight ratio, high surface quality and easy recycling. It is expected that aluminum alloy will act as one of the basic materials in people's daily life and engineering application in the future. 6026 aluminum alloy is a recent developed wrought alloy, with medium-high mechanical properties, good resistance to corrosion, good suitability for hard anodizing, and is mainly subjected to hot forging process.

The hot forming processes on metals and alloys, such as forging, rolling and extrusion, are important steps that determine the dimensional accuracy and mechanical properties of the final product. Hence, a comprehensive study on hot deformation behavior of materials is of great importance to well control the forming process and consequently to obtain high quality products [1,2]. The material flow behavior during hot deformation is often complex, in which both of the work hardening and dynamic softening phenomenon are significantly affected by deformation parameters, such as the strain rate, deformation degree and temperature. Moreover, the metallurgical phenomena such as dynamic recovery and dynamic recrystallization also depends on the given deformation condition, which directly influences the final microstructure [3]. Therefore, a constitutive equation correlating the flow stress, strain, strain rate and deformation temperature becomes an interesting issue for researchers, since it can be used to predict the flow stress and even the microstructure evolution during hot forming processes. On the other hand, the numerical simulation has been widely applied in various metal forming processes to optimize the design of forming tools and process parameters [4–7]. In order to simulate the material flow behavior under specified conditions, a constitutive equation which could mathematically describe the flow stress of the material is generally used as an input code [8–10]. The simulated results can be truly reliable only when a proper constitutive equation is embedded. Hence, a large number of researchers have devoted their efforts on constitutive modeling for various metals and alloys based on the experimental data.

In a recent review on the constitutive descriptions for metals and alloys in hot working, the constitutive models were divided into three categories: phenomenological, physical based and artificial neural network (ANN) models [11]. The phenomenological models involve less material constants in comparison with the physical based ones. Moreover, the required experiments for phenomenological models could be conducted easily [12]. Therefore, various phenomenological models have been developed to predict the flow stress, and among these models, the Johnson–Cook (JC) [13] and Arrhenius models [14] are the most widely used ones.

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* Corresponding author.
E-mail addresses: chenliang@sdu.edu.cn (L. Chen), zhaogq@sdu.edu.cn (G. Zhao).

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The JC model was originally proposed as an empirical constitutive model for metals subjected to large deformation, high strain rate and high temperature, and has the advantages of few material constants, limited required experiments and small calculation quantity. Thus, the JC model has been employed in describing the flow stress of many metallic materials, such as aluminum alloys [15,16], magnesium alloy [12], steels [17–19] and composite materials [20]. However, the original JC model assumes that the thermal softening, strain-rate hardening and strain-hardening are three independent phenomena, and cannot involve their coupled effects [11]. Moreover, the determination of reference condition and the mathematical derivation of temperature coefficient were often inappropriate [21]. Hence, the original JC model usually cannot give precise prediction on the flow stress in many cases. In recent years, some researchers have attempted to propose some modified JC models [15–23], which significantly improve the prediction accuracy.

The hyperbolic sine-typed Arrhenius model considers the coupled effects of deformation temperature and strain rate, which makes it possible to accurately describe the relationship between the flow stress, temperature and strain rate. Up to date, the Arrhenius model has been successfully applied for various materials, such as aluminum alloy [24,25], steel [9,26] and magnesium alloy [27]. However, it is lack of suitability for the materials having obvious dynamic softening during hot deformation, since the influence of strain is not included. In recent years, the researchers have put their efforts on the strain compensated Arrhenius model [27–31], and the prediction accuracy was greatly enhanced.

In this study, the hot deformation behavior of homogenized 6026 aluminum alloy was investigated by conducting isothermal hot compression tests at varying deformation temperatures and strain rates. The initial microstructure of 6026 aluminum alloy was examined and the true stress–strain data was obtained by conducting hot compression tests. Importantly, the experimental measured true stress–strain curves were employed to establish four kinds of constitutive equations, based on the original JC model, modified JC model, Arrhenius model and strain compensated Arrhenius model, respectively. Moreover, the prediction accuracy of these models was evaluated by comparing the predicted and experimental flow stresses. The present study mainly aimed to clarify the hot deformation behavior of homogenized 6026 aluminum alloy, and to make a comparative study on the suitability of different constitutive models.

2. Experimental procedure

The as-cast 6026 aluminum alloy with the chemical compositions (wt.%) of Al–1.0Si–0.65Fe–0.3Cu–0.65Mn–0.79Mg–0.3Cr–0.25Zn was received in the form of rod having the diameter of 152 mm. The as-cast billet was homogenized at 743 K for 24 h and then slowly cooled to room temperature in the air. In accordance with ASTM: E209, the cylindrical specimens of 15 mm in height and 10 mm in diameter were machined from the homogenized billet. The microstructure of the specimen before compression test was examined by etching with the solution of 1.0 ml HF, 1.5 ml HCl, 2.5 ml HNO_3 and 95 ml H_2O, as shown in Fig. 1, from which the coarse equiaxed grains with average grain size of 110 μm could be obviously observed.

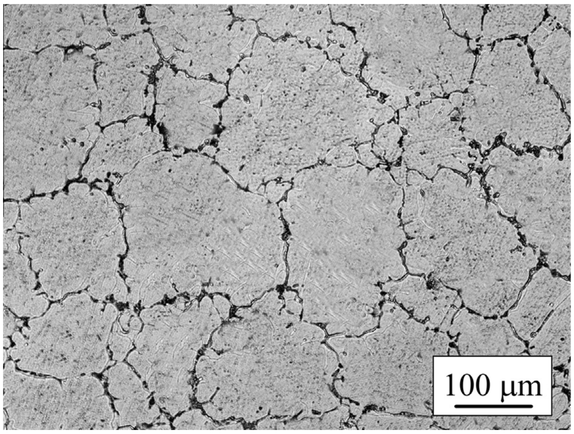

Fig. 1. Microstructure of the homogenized 6026 aluminum alloy.

The hot compression tests were carried out using Gleeble-1500 thermo-simulation machine. The deformation temperatures varied from 673 K to 823 K at an interval of 50 K, and the strain rates were set to be 0.001 s^{-1}, 0.01 s^{-1}, 0.1 s^{-1}, 1.0 s^{-1} and 10 s^{-1}, respectively. The specimens were firstly heated to the deformation temperature at the heating rate of 10 K/s and then held for 5 min to ensure a homogenous temperature distribution throughout the specimen. When the reduction of the specimens reached 60%, the hot compression tests were finished and the deformed specimens were quenched into cool water immediately. The K type thermocouple was spot welded on the middle of the specimen to accurately control the heating speed and measure the specimen temperature. During the hot compression tests, the data of force and stroke was recorded automatically. According to the definition, the true stress and true strain can be calculated as,

$$\sigma = \frac{F}{A_1} = \frac{F}{A_0 l_0} l_1 \tag{1}$$

$$\varepsilon = \ln \frac{l_1}{l_0} \tag{2}$$

where F is the instantaneous force, A_0 is the original cross section, A_1 is the instantaneous cross section, l_0 is the original height, l_1 is the instantaneous height. The graphite foils were used as lubricant between the specimen and die during hot compression tests, since the interfacial friction has some negative effects on the accuracy of the calculated true stress–strain data. In this study, the barreling of specimen is not significant, and thus the effect of friction on flow stress was neglected.

3. Results and discussion

3.1. Flow stress behavior

The true stress–strain curves of homogenized 6026 aluminum alloy obtained from hot compression tests are shown in Fig. 2. For each curve, it can be observed that the flow stress increases rapidly with the strain at the initial stage of hot deformation, which is corresponding to the work hardening phenomenon caused by the rapid increase of dislocation density. After the initial stage, the flow stress reaches the peak point, and then keeps constant or decreases slightly with the increase of strain. The dynamic softening tends to occur with the proceeding of hot deformation, which counteracts the work hardening effect, and thus the flow stress cannot keep rising. When the work hardening and dynamic softening reach a dynamic equilibrium, the dislocation density remains relatively constant and the flow stress becomes steady state [32]. In this study, the softening mechanism might be mainly attributed to dynamic recovery, since aluminum alloy generally yields high stacking fault energy [33]. However, to clarify the occurrence of dynamic recrystallization, some careful examination on the microstructure of the deformed specimens should be carried out, which is out the scope of the present study. Moreover, it is obvious that the peak stress decreases with increasing temperature, which is due to the thermal activation processes that