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Constitutive analysis of homogenized 7005 aluminum alloy at evaluated temperature for extrusion process

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ABSTRACT

Although the extruded profiles of 7005 aluminum alloy have been widely used in the components of high speed train, automobile and aircrafts, the plastic deformation behavior of homogenized 7005 aluminum alloy at evaluated temperature has not been fully clarified. In this study, the isothermal hot compression tests of homogenized 7005 aluminum alloy at the deformation temperatures ranging from 623 K to 823 K and with the strain rates ranging from 0.001 s^{-1} to 10 s^{-1} were conducted for constitutive analysis. It was found that the flow stress increased with decreasing deformation temperatures and increasing strain rates. Two Arrhenius-typed constitutive equations without and with the compensation of strain were developed based on the true stress–strain curves. Although both constitutive equations show their excellent predictability on the flow stress, the one considering the influence of strain has higher accuracy. Furthermore, the extrusion experiment and corresponding finite element simulation using the developed constitutive equation with strain compensation were carried out. The simulated results confirmed that the material flow behavior of the 7005 aluminum alloy during extrusion process was well predicted.

1. Introduction

In recent years, the high strength 7xxx series (Al–Zn–Mg–Cu) aluminum profiles have rapid development, since the extrusion companies are currently shifting the application fields of aluminum profiles from architecture to industry [1–5]. AA7005 as one of the typical 7xxx series aluminum alloys has excellent combination of mechanical properties, high corrosion resistance, good weldability, and the AA7005 profiles have been widely used in the components of high speed train, automobile and aircrafts.

Among the many hot forming processes of aluminum alloy, extrusion has become the primary one due to its high productivity, low material consumption and excellent product quality (high dimensional accuracy and good mechanical properties). Generally, the design of extrusion dies and optimization of process parameters should be based on the comprehensive understanding of material flow behaviors during extrusion process [6–8]. However, the material flow is often complex because the hardening and softening mechanisms are affected by the forming conditions. Thus, a proper constitutive equation correlating stress, strain, strain rate and deformation temperature is of great importance, since it can be used to predict the flow stress and even the microstructure evolution of the material during extrusion [9–11]. Moreover, with the development of computer technology, the numerical simulation has been widely used for extrusion engineers. During the simulation modeling, the constitutive equation of the workpiece is generally used as an input code. The reliability of the simulated results is greatly determined by the accuracy of the embedded constitutive equation.

Due to the importance mentioned above, many researchers have employed hot compression tests to derive the constitutive equations in a broad range of aluminum alloys at evaluated temperature. Lin et al. [12] investigated the deformation characteristic of AA2124-T851 and proposed the revised constitutive equations based on the friction corrected stress–strain curves. Rezaei Ashtiani et al. [13] predicted the constitutive equation considering the compensation of strain for the commercial purity aluminum of AA1070. Wu et al. [14] analyzed the flow behavior of AA7050 during the work hardening and dynamic recrystallization stages divided by the critical strain, respectively. Shi et al. [15] proposed two sets of exponent-typed equations for the forging AA6005A at different deformation temperatures. Rokni et al. [16] analyzed the plastic flow behavior of AA7075 above 723 K and derived different constitutive equations for the material at solid and semi-solid states. Zhang et al. [17] performed hot compression tests to evaluate the effects of initial microstructures on the flow stress of AA2219. Lin et al. [18] proposed a new constitutive model

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considering the effects of strain, strain rate, and deformation temperature to describe the flow behavior of 7075 Al alloy.

In the above open literatures, the Arrhenius equation has been widely used to describe the constitutive relation of aluminum alloys at evaluated temperature. However, it should be noted that little research has been employed on the homogenized 7005 aluminum alloy which was used in the extrusion process. Thus, in this study, the plastic deformation behavior of homogenized 7005 aluminum alloy were investigated by performing isothermal hot compression tests at varying deformation temperatures and strain rates. Relying on the obtained true stress–strain curves, two constitutive equations without and with the compensation of strain were modeled, respectively. Importantly, the extrusion experiment and finite element simulation were performed and compared to verify the accuracy of the modeled constitutive equation. The main objective of the present study is to clarify the flow behavior of homogenized 7005 aluminum alloy in wide range of temperatures and strain rates, and to provide basic data for extrusion simulation.

2. Experimental procedure

The as-cast billet of 7005 aluminum alloy with a diameter of 260 mm was provided by one local extrusion company. The chemical compositions of the investigated 7005 aluminum alloy are given in Table. 1. The homogenization was carried out at 743 K for 48 h and then slowly cooled to room temperature in the air. The homogenized sample was etched with the solution of 1 ml HF, 1.5 ml HCl, 2.5 ml HNO_3 and 95 ml H_2O. Then, the homogenized microstructure along the axial direction of the as-cast billet was examined by means of optical microscope, and the result is shown in Fig. 1. As is seen, very coarse equiaxed grains could be found, and the calculated average grain size is around 180 μm according to **ASTM: E112-13**.

The isothermal hot compression tests were conducted on Gleeble-1500 thermo-simulation machine. In accordance with **ASTM: E209**, the cylindrical specimens with a diameter of 10 mm and a height of 15 mm were cut and machined from the homogenized billet. The experimental temperatures varied from 623 K to 823 K at the 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}. Before applying the load, the specimens were held at the experimental temperature for 3 min to obtain temperature equilibration. The thermocouple was welded on the specimen surface to measure and control the experimental temperature precisely. And the graphite foils were used as lubricant to minimize the friction between the specimen and anvil. The hot compression tests were finished when the true strain exceeded 0.6 and the specimens were dropped into cooled water for quenching.

3. Results and discussion

3.1. True stress–strain curves

Fig. 2 shows the true stress–strain curves of the homogenized 7005 aluminum alloy at various deformation temperatures and strain rates obtained from the isothermal hot compression tests. The deformation behavior at elevated temperature is a competitive process between the work hardening and dynamic softening. At the early stage, the flow stress increases rapidly with increasing strain, which is because of the work hardening caused by the increase density of dislocations and the retardation on the movement of the dislocations. As the deformation proceeds, the flow stress cannot increases continuously with the increasing strain, and reaches the steady state gradually. This phenomenon indicates the occurrence of dynamic softening which could counteract the work hardening effect. Generally, the main softening mechanism of aluminum alloy is dynamic recovery due to its high stacking fault energy which makes the occurrence of dynamic recrystallization difficult. Moreover, the peak flow stresses in the stress–strain curves shown in Fig. 2 are not obvious. Thus, in the present study, it is expected that the main softening mechanism during hot compression of homogenized 7005 aluminum alloy should be dynamic recovery. Such phenomenon that dynamic recovery plays an essential role in softening was also found in the homogenized 7050 aluminum alloy during the hot compression at evaluated temperature [10].

Table 1
Chemical compositions of the as-received 7005 aluminum alloy.

Element	Zn	Mg	Mn	Fe	Si	Cu	Cr	Ti	Zr	Al
(wt%)	4.30	1.65	0.45	0.21	0.32	0.08	0.11	0.06	0.06	Bal.

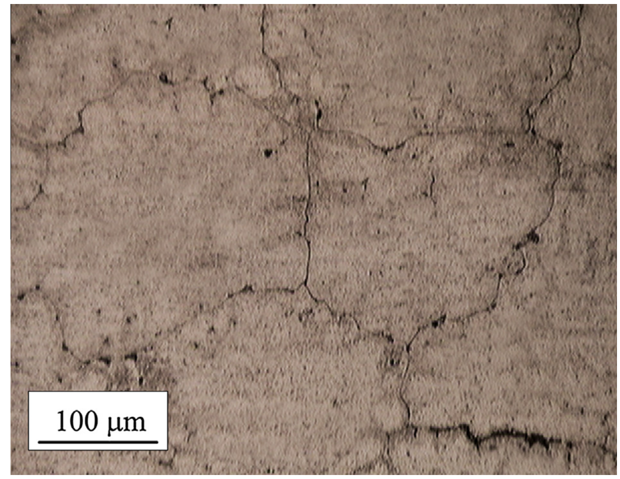

Fig. 1. Optical micrograph of the as-homogenized 7005 aluminum alloy.

On the other hand, both of the peak and steady state flow stresses decrease with the increasing temperature or decreasing strain rates. This is because the higher temperature makes the occurrence of dynamic softening readily and obviously at a given strain rate. On the other hand, higher strain rates make the phenomenon of dislocation hardening more severe.

3.2. Constitutive modeling

The constitutive equation could be used to describe the plastic deformation behavior and to calculate the flow stress of one material. And it has been found that the hot deformation process of many alloys is similar to the creep process, where the thermal activation phenomenon appears in the hot deformation process. Although several empirical models have been developed, it was proved that the Arrhenius equations can accurately describe the relationship between the strain rate, deformation temperature and flow stress [19–21]. This can be expressed as:

$$\dot{\varepsilon} = A_1 \sigma^{n_1} \exp\left(-\frac{Q}{RT}\right) \quad (1)$$

$$\dot{\varepsilon} = A_2 \exp(\beta\sigma) \exp\left(-\frac{Q}{RT}\right) \quad (2)$$

where $\dot{\varepsilon}$ is the strain rate (s^{-1}), σ is the flow stress (MPa), Q is the activation energy of hot deformation (kJ mol^{-1}), R is the universal gas constant (8.31 J mol^{-1} K^{-1}), T is the absolute temperature (K), A_1, A_2, β and n_1 are the material constants. The power law of Eq. (1) is used in low stress level when $\alpha\sigma < 0.8$, where α is defined