Materials Science & Engineering A 571 (2013) 83–91

Contents lists available at SciVerse ScienceDirect

Materials Science & Engineering A

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

Evolution of activation energy during hot deformation of AA7150 aluminum alloy

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ARTICLE INFO

Article history:
Received 19 December 2012
Accepted 25 January 2013
Available online 9 February 2013

Keywords:
AA7150 aluminum alloy
Hot compression deformation
Microstructure
Constitutive equation
Activation energy

ABSTRACT

The hot deformation behavior of a homogenized AA7150 aluminum alloy was studied in compression tests conducted at various temperatures (573–723 K) and strain rates (0.001–10 s^{-1}). The flow stress behavior and microstructural evolution were observed during the hot deformation process. A revised Sellars' constitutive equation was proposed, which considered the effects of the deformation temperature and strain rate on the material variables and which provided an accurate estimate of the hot deformation behavior of the AA7150 aluminum alloy. The results revealed that the activation energy for the hot deformation of the AA7150 aluminum alloy is not a constant value but rather varies as a function of the deformation conditions. The activation energy for hot deformation decreased with increasing deformation temperature and strain rate. The peak flow stresses under various deformation conditions were predicted by a revised constitutive equation and correlated with the experimental data with excellent accuracy.

1. Introduction

The 7xxx aluminum alloys with a high strength-to-density ratio and excellent mechanical fracture toughness have been widely used in the aircraft and aerospace industries [1]. These aluminum alloys are generally subjected to hot-forming processes such as rolling, forging and extrusion. Mechanical properties are affected by the chemical composition, strain history and microstructure resulting from thermomechanical processing. The flow behavior of aluminum alloys during hot deformation is of great importance for the design of metal-forming processes due to its effective role in the required deformation energy as well as in the kinetics of metallurgical transformations, such as dynamic recovery (DRV) and dynamic recrystallization (DRX) [2,3]. Furthermore, the flow behavior is influenced by thermomechanical factors such as the degree of deformation, strain rate and deformation temperature [2].

A constitutive relation is generally used to describe the plastic flow properties of metals and alloys, which are correlated with the flow stress, strain rate and deformation temperature. Several models have been proposed to describe the hot deformation behavior, including physical-based, phenomenological and artificial neural network models and equations [4–13]. Sellars and McTegart [4] developed a hyperbolic-sine constitutive law to describe the hot working and creep behavior of aluminum, nickel, copper and steel materials. Johnson and Cook [5] proposed a phenomenological model, which Lin et al. [6] then modified to evaluate the hot compressive behavior of a 7075 aluminum alloy by considering the effects of strain rate and the deformation temperature. Chai et al. [7] conducted a comparative study on the capability of a back propagation neural network model and a strain-compensated, Arrhenius-type constitutive equation to represent the elevated temperature flow behavior of XC45 steel. Lin et al. [8] proposed a revised Arrhenius constitutive equation to describe the effect of strain on material constants and on the flow behavior of 42CrMo steel. In addition, some researchers have applied these constitutive models and equations to evaluate the hot deformation behavior of various metals and alloys [9–13].

With various constitutive models and equations available, the hyperbolic-sine law, proposed by Sellars and McTegart [4], has been proven to be most applicable over a wide range of stresses. The activation energy of a material for hot deformation derived from this relation is usually used as an indicator of the degree of difficulty of the hot deformation process. It may provide a guideline for optimizing the hot working process and also furnish additional information on the microstructure and flow stress evolution in successive deformation processes. In majority of research on the hot deformation behavior of materials [4–13], the activation energy has been treated as a constant value for all applied hot deformation conditions. In fact, the activation energy of an aluminum alloy for hot deformation represents mainly the

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http://dx.doi.org/10.1016/j.msea.2013.01.080

free energy barrier to dislocation slipping on slip planes. As the energy required for dislocation slipping is affected by the temperature and external stress during hot-forming processes [2,14], the activation energy for hot deformation cannot remain constant, but should instead be a function of the main deformation parameters, including deformation temperature and strain rate. However, the effects of deformation temperature and strain rate on the evolution of activation energy have rarely been reported. Moreover, the thermodynamic mechanism of evolution of the activation energy under different deformation conditions has not been clarified.

In the present paper, the hot deformation behavior of a homogenized AA7150 alloy is studied using hot compression tests performed at various temperatures and strain rates. Considering the effect of deformation temperature and strain rate, a revised Sellars' constitutive equation is proposed to predict the hot deformation behavior of an AA7150 aluminum alloy. The evolution of the activation energy for hot deformation under various deformation conditions is described.

2. Experimental

The experiments were conducted on an AA7150 aluminum alloy, which was taken as the starting material in the form of cylindrical DC cast billets. Approximately 3 kg of materials was remelted in an electrical resistance furnace and then cast into a rectangular permanent steel mold measuring $30 \times 40 \times 80$ mm^3. The chemical composition of the alloy used is given in Table 1. The cast ingots were homogenized at 738 K for 24 h, followed by a direct water quenching. Small cylindrical samples 10 mm in diameter and 15 mm long were machined from the homogenized ingots. Uniaxial compression tests were conducted on a Gleeble 3800 thermomechanical simulation unit at strain rates of 0.001–10 s^{-1} and deformation temperatures of 573–723 K. During the tests on the Gleeble unit, the samples were heated to the desirable deformation temperature at a heating rate of 10 K/s and held at that temperature for 3 min prior to compression. The samples were deformed to a total true strain of 0.8 and then immediately water-quenched.

All deformed samples were sectioned parallel to the compression axis along the centerline and then polished and etched in the Keller solution for observation under an optical microscope. The microstructure of the as-homogenized material was also examined prior to hot deformation. Additionally, some samples were selected for analysis using the electron backscattered diffraction (EBSD) technique with a scanning electron microscope (SEM, JEOL JSM-6480LV). In the EBSD analysis, the boundaries of both the grains and subgrains are defined as low angle boundaries (LAB), medium angle boundaries (MAB) and high angle boundaries (HAB) for which the angles of boundary misorientation occur in the ranges of 1–5°, 5–15° and greater than 15°, respectively [15]. The step size between the scanning points was set to 1.0 μm for the deformed grain structure. In addition, the EBSD analysis was performed to measure the grain size of the as-homogenized sample using the linear intercept method [16]; a surface area of approximately 10 mm^2 with a scanning step size of 5.0 μm was selected for the sample.

Table 1
Chemical composition of the 7150 aluminum alloy studied.

Material	Chemical compositions (wt%)						
	Zn	Mg	Cu	Si	Fe	V	Al
AA7150 alloy	6.44	2.47	2.29	0.16	0.15	0.01	Bal.

3. Results and discussion

3.1. Flow stress behavior

The true stress–true strain curves obtained during hot compression of the 7150 aluminum alloy at strain rates of 0.001–10 s^{-1} and at deformation temperatures of 573–723 K are presented in Fig. 1. In general, the flow stresses increased rapidly at the beginning of deformation and then either remained fairly constant or decreased to some extent after attaining the peak stress. At the early stages of deformation, dislocations multiplied dramatically, and the work hardening process was predominant, thereby leading to a rapid increase in the flow stress. As the dislocation density increased, dynamic softening occurred, which can offset the effect of work hardening; thus, the flow stress increased at a decreasing rate until the peak stress was reached. Subsequently, the flow stress either decreased with increasing strain or remained steady. The former behavior is observed when the rate of dynamic softening is higher than that of work hardening. In this case, the peak stress is defined as the maximum value of the flow stress curve at which a distinct peak appears (indicated by an arrow in Fig. 1(a)). The latter behavior occurs as a result of a dynamic equilibrium between work hardening and dynamic softening, in which the peak stress was identified as the tangent point on the flow curve by the extension of a line along the steady-state flow stresses (indicated by an arrow in Fig. 1(b). It is evident that the level of both the peak stress and the flow stress increased with increasing strain rate and with decreasing deformation temperature. The peak stress was highest (189 MPa) at a strain rate of 10 s^{-1} and at a deformation temperature of 573 K, whereas the lowest peak stress (18 MPa) was obtained at a strain rate of 0.001 s^{-1} and at a temperature of 723 K. For a given strain rate, the driving force for dynamic softening which counteracts work hardening was reduced with decreasing temperature [2], thereby leading to an increase in both the peak stress and the overall flow stress. On the other hand, for a given temperature, the greater the strain rate, the higher the peak stress and the flow stress. It has been reported that the higher multiplication of dislocations and the formation of tangled dislocation structures, as barriers to dislocation movement, were caused by an increase in the strain rate [2]. These observations are in good agreement with earlier reports on 7xxx alloys [6,17–19].

3.2. Microstructural evolution

Fig. 2 illustrates the initial grain structure of the homogenized 7150 alloy prior to hot compression, as well as some representative microstructures deformed under various conditions. Fig. 2(a) reveals that the homogenized alloy is composed of uniform equiaxed grains that originate from the casting. The average grain size was 127 μm. During hot compression, the original grains were plastically elongated perpendicular to the compression direction. When the alloy was deformed at 573 K and 10 s^{-1} (Fig. 2(b)), the original grains were severely torn and broke into irregular deformation bands due to deformation occurring on different slip systems [15]. As the deformation temperature increased to 673 K with a strain rate of 10 s^{-1} (Fig. 2(c)), the deformation became more homogeneous, with fewer large-scale deformation bands visible under the optical microscope, which was the result of an increase in the number of operating slip systems and an increasing level of dynamic recovery as the temperature increased [20]. Moreover, when the strain rate was lowered to 0.01 s^{-1} at 673 K, the original grain boundaries became serrated along which subgrains became visible (Fig. 2(d)). This morphology is related to the migration of high angle grain boundaries in response to both the boundary tensions of the substructure and to variations in dislocations, which indicates a stronger dynamic recovered structure