Materials and Design 51 (2013) 592–597

Contents lists available at SciVerse ScienceDirect

Materials and Design

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

The effects of grain size on the hot deformation and processing map for 7075 aluminum alloy

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ARTICLE INFO

Article history:
Received 27 January 2013
Accepted 11 April 2013
Available online 22 April 2013

Keywords:
Aluminum alloy
Flow stress
Processing map
Dynamic recovery
Dynamic recrystallization
Grain size

ABSTRACT

The effects of grain size on hot deformation and processing map of 7075 aluminum alloy were investigated using Gleeble-1500 test machine at 320–480 °C with strain rates from 0.001 to 1 s^{-1}. The microstructural evolution observations of the alloy were carried out using ZESIS optical microscopy. The results showed that the flow stress increased with increasing strain rate and decreasing temperature. The flow stress of the alloy with coarse grains was higher than that of the alloy with fine grains. During hot-deformation, the alloy exhibited dynamic recovery at temperatures ranging from 320 to 440 °C and dynamic recrystallization at 480 °C. The processing maps for the alloy with different grain sizes were built at a strain of 0.6. It was found that the characteristics of the two processing maps were different. The instability deformation domain occurred at temperatures between 320 and 340 °C and at a strain rate of 0.18–1 s^{-1} for the alloy with coarse grains, but at temperatures between 380 and 420 °C and also at a strain rate of 0.18–1 s^{-1} for the alloy with fine grains. Based on the processing maps and microstructure observations, the optimum hot-working parameters were determined to be 480 °C at 0.1 s^{-1} for the coarse alloy and 480 °C at 0.01 s^{-1} for the fine alloy. The optimized hot working parameters of 7075 aluminum alloy with different grain size could be used in various hot working processes.

1. Introduction

To reduce pollution, there is increasing trend to replace steels with light-weight high strength aluminum alloys [1]. Among various series of high strength aluminum alloys, the 7xxx series (Al–Zn–Mg–Cu alloy system) possess superior properties such as relatively low density, high specific strength [2] and good resistance to stress corrosion cracking (SCC) [3]. There is extensive research on the high temperature plastic deformation behavior of the 7xxx series Al alloys to determine the optimum fabrication conditions. However, most of these works focused on the effects of temperature, strain rate and strain on deformation flow behavior [4–6] and processing map [7,8] and there was little work investigating the effect of initial grain size on the hot working behavior and processing map of 7xxx aluminum alloys.

It is important to understand the effect of initial grain size on flow stress behavior of a metallic material during hot-working in order to establish the optimum processing conditions and improve mechanical properties. There have been a number of studies on the effects of initial grain size on flow stress behavior of many metallic materials such as commercial pure aluminum [9], 2219 aluminum alloy [10], magnesium alloys [11,12], steels [13], and stainless steels [14]. These studies indicated that flow stresses increase with decreasing grain size at a given strain and strain rate at ambient temperature as suggested by the Hall–Patch equation. However, at elevated temperature, flow stresses tend to decrease with decreasing grain size at a given strain and strain rate, especially under low strain rates.

Flow stress is the most important parameter for characterizing plastic deformation properties of metallic material. It determines the load and energy required during plastic deformation. The processing map based on the dynamic materials model (DMM) is considered to be an important model for optimizing the hot working parameters. By using the processing map, the plastic deformation mechanisms in various deformation conditions and the unstable deformation zones can be predicted. Because of its importance, the DMM based processing map has been widely used to predict hot workability of metallic materials.

The DMM based processing map was established by Prasad and co-workers [15–18]. According to Prasad, the hot deformation work could be considered as power dissipater. The total power P consists of two complementary parts: G represents the power dissipation through plastic deformation, most of which are converted into heat, and J represents the power dissipation through microstructure transition, such as dynamic recovery, dynamic

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http://dx.doi.org/10.1016/j.matdes.2013.04.034

recrystallization, as well as damage of the material. According to this phenomenological model, G and J are related to the parameter m (the strain rate sensitivity) as below:

$$\left(\frac{\partial J}{\partial G}\right)_{\varepsilon,T} = \frac{\partial P}{\partial G}\frac{\partial G}{\partial J} = \frac{\sigma d\dot{\varepsilon}}{\dot{\varepsilon} d\sigma} = \left[\frac{\partial(\ln\sigma)}{\partial(\ln\dot{\varepsilon})}\right]_{\varepsilon,T} = m \tag{1}$$

For an ideal linear dissipating body, $m = 1$ and $J = J_{\max} = \sigma\dot{\varepsilon}/2 = P/2$, and the power-dissipation capacity of the material can be estimated by the efficiency of power dissipation η, which is given by:

$$\eta = \frac{J}{J_{\max}} = \frac{2m}{m+1} \tag{2}$$

The instability map was developed on the basis of the extreme principle of irreversible thermodynamics applied to large plastic flow body. The onset of a flow instability criterion was defined below on the basis of power dissipation principle:

$$\xi(\dot{\varepsilon}) = \frac{\partial \ln(m/m+1)}{\partial \ln\dot{\varepsilon}} + m < 0 \tag{3}$$

The dependence of the instability parameter $\xi(\dot{\varepsilon})$ on temperature and strain rate can be expressed by the instability map.

In this study, the effect of initial grain size on hot-working behavior of 7075 aluminum was investigated. Based on the experimental results, processing maps for the alloy with two different grain sizes were established.

2. Experimental procedures

The chemical composition of the 7075 aluminum alloy studied in this work was composed of 6.08-Zn, 2.67-Mg, 1.26-Cu and 0.14-Cr. The cast ingots of the alloy, with 100 mm in diameter and 100 mm in height, were homogenized at 480 °C for 24 h and then cooled down to room temperature in air. They were then subjected to extrusion under different extrusion ratios at 400 °C to produce microstructures with different grain sizes. The microstructures of the extruded 7075 alloy bars with extrusion ratios of 4 and 16 were shown in Fig. 1. It can be seen that the grains of the bars with different extrusion ratios were both elongated in the extrusion direction, with the bar experiencing a higher extrusion ratio having finer grain sizes. The average widths (in the compression direction) of the grains for the bars with lower and higher extrusion ratios were approximately 50 μm and 20 μm, respectively. Hot compression tests were subsequently performed to investigate the hot deformation behavior of the material. Cylindrical specimens of ∅8 mm × 12 mm were machined from the extruded bars with the longitudinal axis of the specimens parallel to the axis direction of the bars and the hot-compression tests were carried out in accordance with ASTM: E209.

Hot-compression tests were carried out using a Gleeble-1500 thermal simulation machine in the temperature range 320–480 °C and in the strain rate range 0.001–1 s^{-1}. The experiments were repeated for three times. The specimens were induction-heated to the deformation temperature within 30 s and held for 5 min to obtain a stable and uniform temperature prior to deformation. All specimens were compressed to a true strain of about 0.7, and then water-quenched to room temperature. The test specimens were sectioned parallel to the loading axis, polished and etched using an acidic solution (10 ml H_2O, 10 ml HNO_3, 10 ml HCl and 5 ml HF) for optical microscopic observation.

3. Results and discussion

3.1. Flow stress behavior

The true stress–strain curves accompanying error bars of the 7075 aluminum alloy with different initial grain sizes at various temperatures and strain rates are presented in Fig. 2. The signs c and f in Fig. 2 represent coarse and fine grains, respectively. The following can be seen from the figure:

Deformation temperature and strain rate had clear effects on the flow stress behaviors of the Al alloy with different microstructures. The flow stress decreased with increasing temperature at a given strain rate and with decreasing strain rate at a given deformation temperature. The flow stress curves wave at high strain rates, indicating unstable balance between two processes which occur simultaneously during plastic deformation of metals at elevated temperatures: work hardening due to built-up of dislocations and softening due to dynamic recovery and/or recrystallization [19].

It is of interesting to note that the flow stress increased with increasing grain size at high temperature. This was different from the effect of grain size on tensile strength at room temperature. This might be attributed to the change from dislocation glide (DG) dominant to grain boundary sliding (GBS) dominant deformation mechanism when temperature is high and grain size is reduced. This change could effectively reduce flow stress, resulting in a behavior different from that described by the Hall–Petch equation for DG deformation mechanism [20]. The decreasing flow stress with decreasing grain size was also related to the fact that a microstructure with finer grain sizes has more grain boundary per unit area compare with that of coarse grain boundaries, therefore finer grain could provide more nucleation sites at grain boundaries for DRX during hot deformation, resulting in faster DRX and hence lower flow stress.

3.2. Processing map

The relationship between $\log\dot{\varepsilon}$ and $\log\sigma$ data was described using a cubic spline function at a strain of 0.6, and the strain rate sensitivity, m, was calculated as a function of strain rate. This was repeated at five different deformation temperatures 320–480 °C.

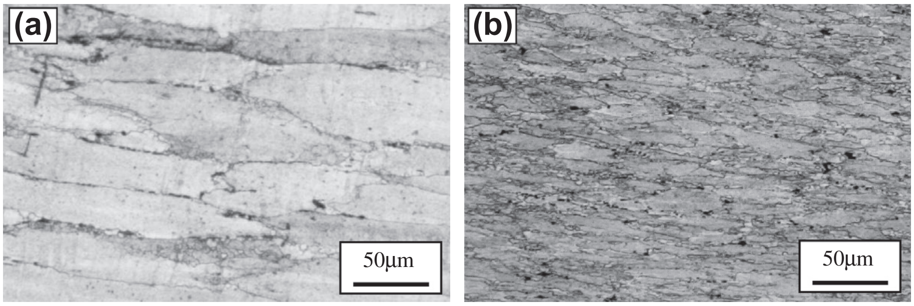

Fig. 1. The microstructure of the extruded 7075 aluminum alloy bar with different extruded ratios (a) 4; (b) 16.