Journal of Alloys and Compounds 674 (2016) 26–36

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Constitutive behavior of aluminum alloy in a wide temperature range from warm to semi-solid regions

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A R T I C L E I N F O

Article history:
Received 23 January 2016
Received in revised form
24 February 2016
Accepted 29 February 2016
Available online 2 March 2016

Keywords:
Constitutive behavior
Aluminum alloys
Semi-solid processing
Deformation
Microstructure

A B S T R A C T

The constitutive behavior of aluminum alloy 7075 was characterized using compression tests performed over a wide range of temperatures (350–600 °C, from warm deformation temperature to semi-solid region) and strain rates (10^{-3}–1 s^{-1}). This work is of significance for the development of compound forming which combines plastic forming and semi-solid processing. The constitutive behavior in the wide temperature range was divided into two types: plastic deformation when the alloy is in solid state and containing a small fraction of liquid (350–490 °C); thixotropic deformation when the alloy is in the semi-solid state (above 490 °C). An adjusting factor which denotes the effect of liquid on the constitutive behavior was proposed. The constitutive model of peak stress as a function of temperature and strain rate was obtained for the wide range of temperatures (350–600 °C). The average relative errors between the calculated and measured values are 3.88% (350–490 °C) and 4.189% (above 490 °C), respectively.

1. Introduction

Semi-solid processing (SSP) is a promising near net shape technology which can form complex components with relatively high mechanical properties (compared with as-cast part). SSP is based on the thixotropic behavior of materials (e.g. metallic alloys and metal matrix composites) in the semi-solid state [1]. When the materials are sheared they flow like liquid, while when allowed to stand they thicken up again [2,3]. However, semi-solid processing can hardly provide as high mechanical properties as forging [4], and it is mainly attributed to two reasons: (a) the alloy contains some liquid phase (liquid fraction of 40%~60%) before semi-solid processing, so the solidification of intergranular liquid can degrade the bonding strength between solid–solid grains; (b) the improvement in mechanical properties caused by work hardening is little in semi-solid processing. Therefore, a challenge for semi-solid processing is further improving the mechanical properties to compete with the wrought parts.

Combination of plastic forming and semi-solid processing (compound forming) is a feasible method. Two routes can be applied for compound forming: (a) the alloy is pre-formed in the semi-solid state firstly, and as the temperature decreased below the solidus it is deformed plastically to the final shape; (b) the billet is rapidly heated by gradient induction heating before processing, and some region is reheated into the semi-solid state while the temperatures of other regions are still below the solidus. Therefore, thixotropic flow and plastic flow exist simultaneously during the compound forming process.

Constitutive behavior of engineering materials is of importance to predict the flow stress as a function of material structure, temperature and strain rate, and is significant for optimizing the processing parameters [5]. Therefore, constitutive behavior has received much attention in recent decades, and much work has been done to study the constitutive behaviors related to forging or semi-solid processing [6]. Serajzadeh et al. [7] studied the deformation behavior of a metal matrix composite AA2017-10% SiC_p in warm and hot deformation regions (room temperature to 400 °C). At temperatures lower than 250 °C, negative strain rate sensitivity was observed indicating the occurrence of dynamic strain aging, while at higher temperatures, dynamic recovery was detected and the apparent activation energy for hot deformation was calculated to be ~303 kJ/mol. Roy et al. [8] studied the constitutive behavior of as-cast A356 aluminum alloy using compression tests performed over a wide range of deformation temperatures (30–500 °C). The results indicate that the extended Ludwik-Hollomon and Koccks-

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http://dx.doi.org/10.1016/j.jallcom.2016.02.254
0925-8388/

Mecking are suitable for small strain and large strain conditions, respectively. At elevated temperatures, Zener-Hollomon model provides the best prediction of flow stress. Wang et al. [9] proposed a visco-plastic constitutive equation for thixoforming aluminum alloy in the semi-solid state, and it takes into account the effect of the liquid fraction along with other factors i.e. the stress/strain relationship, strain rate and temperature.

To the best of our knowledge, although many phenomenological and physical-based constitutive models have been proposed for forging and semi-solid processing, no constitutive model has been reported to cover the wide range of processing temperatures (from warm forming temperature to semi-solid region). Therefore, it will be of significance to develop a constitutive model suitable for compound forming which combines plastic forming and semi-solid processing.

In the present work, the constitutive behavior of aluminum alloy was characterized using compression tests performed over a wide range of temperatures (350–600 °C). Mechanical testing and microstructural observations were adopted to evaluate the materials responses during deformation at elevated temperatures. This work could enable optimization for the practical application and numerical simulation of compound forming.

2. Experimental procedure

The materials used in this work were extruded and T6 heat treated 7075 aluminum alloy rods (extruded at 350 °C with extrusion ratio of 16:1). Table 1 shows the chemical composition of the starting materials, which was examined using X-ray fluorescence spectrometer.

Differential scanning calorimetry (DSC) was used to determine the solidification interval and the liquid fraction-temperature relationship. The details of DSC method were described in the previous work [10]. Fig. 1 shows the change in liquid fraction with temperature. The solidus temperature is determined to be 479 °C, and the liquid fraction increases rapidly when temperature is above 540 °C.

Cylindrical samples with diameter of 8 mm and height of 12 mm were cut from the extruded rods with their long axis parallel to the extrusion direction. The compression tests were performed using a Gleeble-1500D thermo-mechanical simulator at various temperatures from 350 °C to 600 °C and strain rates of 0.001 s^{-1} to 1 s^{-1}. A graphite lubricant was used to reduce the deformed friction between clamps and sample. The compression samples were reheated to the predetermined temperature with a heating rate of 100 °C/min, and isothermally held for 60 s on reaching the target temperature to eliminate thermal gradient.

After the compression tests, the samples were sectioned for microstructural examination. Samples for optical metallography (OM) were prepared by standard technique of grinding with SiC abrasive and polishing with a diamond spray (0.5 μm), and then etched for about 20 s with 2.5%HNO_3-1.5%HCl-1%HF aqueous solution.

Table 1
Chemical composition of 7075 aluminum alloy.

Element	Zn	Mg	Cu	Cr	Si	Mn	Fe	Al
wt %	5.65	2.18	1.71	0.32	0.36	0.28	0.61	Bal.

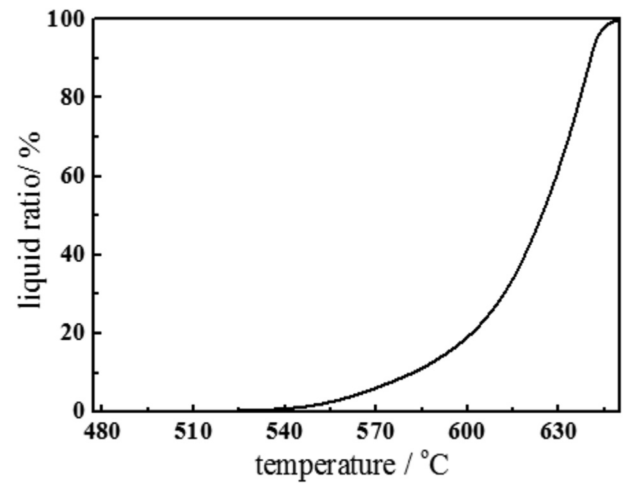

Fig. 1. Liquid fraction (f_l) vs. temperature curve of 7075 aluminum alloy.

3. Results and discussion

3.1. Microstructures of the starting materials

Fig. 2 shows the microstructures of extruded 7075 aluminum alloy in longitudinal and transverse sections. As shown in Fig. 2(a), the grains are elongated with some dispersed particles along the extrusion direction. Some sub-grains also exist in the microstructures in transverse and longitudinal sections, indicating the alloy has been partly recrystallized after T6 heat treatment. According to recrystallization and partial melting (RAP) route [11], if such materials are reheated into the semi-solid state, recrystallization will be stimulated by liquid at high temperatures, and the liquid phase can penetrate the recrystallized boundaries to form spheroidal microstructures which are suitable for semi-solid processing [2]. Therefore, cold or warm worked alloys are usually adopted as the starting materials for semi-solid processing and only need reheating.

3.2. Stress/strain response in the wide range of temperatures

Fig. 3 shows the true stress–strain curves of 7075 aluminum alloy at various deformation temperatures and strain rates. The constitutive behavior exhibits significant difference between two temperature ranges of 350–490 °C (Fig. 3(a)-(e)) and 510–600 °C (Fig. 3(f)-(j)). As shown in Fig. 3(a)-(e), the stress/strain response exhibits typical plastic deformation characters: at the initial stage of deformation, the flow stress first increases linearly (elastic deformation stage) until the yield stress is reached, and increases rapidly (due to work-hardening effect) to the peak stress (the corresponding strain is about 0.03); subsequently, the flow stress seems to be in a steady state and decreases slightly as the strain increasing, indicating a dynamic balance state is attained under the comprehensive effects of work-hardening and softening due to dynamic recovery and recrystallization. As shown in Fig. 3(f)-(j), although the flow stresses increase linearly as the strain increasing, the slopes are smaller than that compressed lower temperatures (Fig. 3(a)-(e)), indicating the elastic modulus decreases in the semi-solid state. Besides, the phenomenon of yielding is not obvious. The striking feature is that the flow stress decreases rapidly after reaching the peak value, and then presents a dynamic balance state. The stress/strain response exhibits typical semi-solid deformation characters: at the initial stage, most of solid grain boundaries have not been penetrated or wetted by liquid phase, so elastic and plastic