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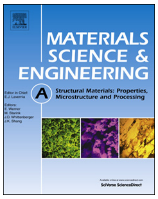

Constitutive characteristics and microstructure evolution of 7150 aluminum alloy during isothermal and non-isothermal multistage hot compression

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ABSTRACT

Isothermal and non-isothermal multistage hot compression tests were carried out on 7150 aluminum alloy at temperature range of 325–425 °C and strain rate range of $0.01-1\ s^{-1}$. During isothermal multistage hot compression, the flow stress decreased with increasing temperature, accumulative strain as well as decreasing strain rate and pass strain. However, the interval time had a complex influence on flow stress, which ascended flow stress values with increasing interval time at 425 °C. The isothermal and non-isothermal constitutive characteristics were studied based on hyperbolic-sine law, indicating complex influences of various processing parameters on material constants. Non-isothermal multistage flow stresses were found to be easier than normal continuous single pass method to manipulate for constitutive equations calculation with better linear fitting reference and comparable activation energy. Precipitation at low temperature and its dissolution at high temperature were found to affect flow behavior and constitutive characteristics remarkably based on microstructural observation of deformed sample.

1. Introduction

Al–Zn–Mg–Cu superhigh strength aluminum alloys are widely used in the aircraft and aerospace industries due to their high strength-to-density ratio and excellent mechanical fracture toughness. Thermomechanical processing of Al–Zn–Mg–Cu alloys has been studied extensively in recent years by using hot compression tests to characterize flow behavior with different process parameters. During thermomechanical processing, mechanical properties of alloys are affected by the chemical composition, strain history and microstructure. When aluminum alloys are strained at the elevated temperature, they may experience work hardening and flow softening which are resulted from dynamic recovery (DRV), dynamic recrystallization (DRX) or dynamic precipitation transformations [1–3]. Therefore, the flow curves, which are the integrated results of the interaction and sequence of these phenomena, are of great importance for designing and optimizing metal-forming processes. The relationship between microstructure and deformation parameters (strain, strain rate and temperature) can be established by analyzing flow curves from laboratory physical simulation tests. Hot torsion, plane strain compression and axisymmetric uniaxial compression are generally adopted to understand metal's fundamental hot deformation behavior over a wide range of deformation parameters with high efficiency and low expenses [1,2].

The effect of deformation temperature (T) and strain rate ($\dot{\varepsilon}$) on hot deformation behaviors can be combined by the Zener–Hollomon parameter (Z) as [1–3]:

$$Z = \dot{\varepsilon}\, exp(\frac{Q}{RT}) \tag{1}$$

where Q is the apparent activation energy for the elevated temperature deformation and R is the gas constant ($8.31\ J\ mol^{-1}\ K^{-1}$). The constitutive equations, shown in Eqs. (2)–(4), were first introduced to describe creep phenomena, which were generally recognized in many cases of hot deformation of metals [1–3]:

$$\dot{\varepsilon} = A'\sigma^{n_1} exp(-\frac{Q}{RT}) \tag{2}$$

$$\dot{\varepsilon} = A'' exp(\beta\sigma) exp(-\frac{Q}{RT}) \tag{3}$$

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$$\dot{\varepsilon} = A[sinh(\alpha\sigma)]^n exp(-\frac{Q}{RT}) \quad (4)$$

where $A'A''A'$, n_1, n, β and α are material constants and σ is the flow stress. Generally, the power law (Eq. (2)) is appropriate for low Z, while for high Z, the exponential law (Eq. (3)) is more suitable. The hyperbolic-sine law (Eq. (4)), meanwhile, can cover a wide range of Z. The constitutive equations used in most studies were usually calculated from the peak stress values, which always assumed that the flow stress was independent of strain (ε) during continuous isothermal tests [2–7]. In order to better understand the flow behavior varied with strain and predict flow stress by constitutive analysis, the variations of constitutive material constants with increasing strain were also explored based on continuous isothermal tests by many researchers [8–11]. A valid characterization of the variation of n and Q with strain could be used effectively to describe the relationships of flow stress between strain, strain rate and temperature. Practically, determination of the strain exponent and fitting the equation to the experimental data always poses certain difficulties.

Most industrial hot working operations, such as rolling and forging, are comprised of several stages deformation, which combine dynamic softening during deformation and static restoration (static recovery (SRV) and static recrystallization (SRX)) during intervals [1,12–17]. In multipass hot working operations, the interpass static restoration (or softening) additionally modifies the form of the flow curve relevant to the subsequent passes and final microstructure. The softening degree depends upon the pass strain, strain rate, temperature, interval time (Δt) and cooling rate. The constitutive equations had been applied to multi-stage simulations of the declining temperature processing schedule which results in a series of flow stress curves, which was firstly reported by Ryan and McQueen [12]. And the effects of interval time, cooling rate and total solute content have been evaluated for various steels subsequently [2,13–15].

In present work, isothermal continuous and multistage hot compression tests were firstly carried out to gain the fundamental constitutive characteristics of 7150 aluminum alloy under various (pass) accumulative strains and interval time. Then non-isothermal (continuous cooling) hot compression tests were also adopted to simulate industry fabrication processing and constitutive characteristics analysis. The constitutive characteristics and related mechanism during isothermal and non-isothermal hot compression tests were discussed based on microstructure characterization.

2. Experimental procedure

The experiments were carried out on the commercial 7150 aluminum alloy with main chemical compositions 6.38Zn, 2.32Mg, 2.11Cu, 0.09Zr, 0.06Si, 0.08Fe, 0.053Ti and Al balance (mass, %). Cylindrical specimens, 10 mm in diameter and 15 mm in height, were machined from the homogenization treated industry ingot (air cooling). The average size of equiaxial grains of the as-received homogenized ingot is approximately 69 μm as shown in Fig. 1(a). Lots of second phase particles are also presented by scanning electron microscope (SEM) in Fig.1(b) due to low cooling rate after homogenization. Continuous (single pass), interrupted isothermal (3 passes and 6 passes) and non-isothermal (6 passes, continuous cooling) multistage axisymmetric uniaxial compression tests were carried out on the Gleeble-3500 thermal simulation machine to the total true strain of 1.2. The deformation temperatures were 325 ºC, 375 ºC and 427 ºC, and the strain rates were 0.01 s^{-1}, 0.1 s^{-1} and 1 s^{-1} with equal pass strain. The interval times (Δt) between passes of the critical multistage compression test were always 10 s or 100 s. During each interval between passes, the deformed sample was stress relaxed for 10 s or 100 s. During the stress relaxation, the temperature was controlled to within ±1 °C by the thermo coupled-feedback-controlled AC current and the load was monitored continuously. All the samples were heated to deformation temperature with a heating rate of 2.5 °C/s and held at that temperature for 180 s to keep temperature uniformly by thermo coupled-feedback-controlled AC current before compression. While the non-isothermal multistage tests were also consisted of pre-heating samples to 425 ºC for 180 s, before gradually cooling down to 325 °C during 6 passes deformation with equal pass strain of 0.2 and interpass intervals of 10 s. The strain rates were 0.01 s^{-1}, 0.1 s^{-1} and 1 s^{-1} respectively. The 0.12 mm thick graphite foil disc with diameter of 16 mm was inserted between the ISO-T anvils. The specimen was lubricated by the graphite foil during uniaxial compression testing, which was recommended by the Dynamic Systems Incorporated (DSI). The negative effects of interface friction were corrected by the method proposed by Ebrahimi and Najafizadeh [18,19]. The deformed microstructures were sectioned parallel to the compression axis along the direction of centerline and prepared for optical microstructure (OM) observations on the Axiovert-40 metallographic microscope by the conventional methods (etched by Keller's reagent) and transmission electron microscope (TEM) microstructure observations on JEOL JEM-3010 transmission electron microscope operating at 300 kV after electropolishing in a solution of 30% HNO_3 and 70% methanol at 25 V and at −30 °C.

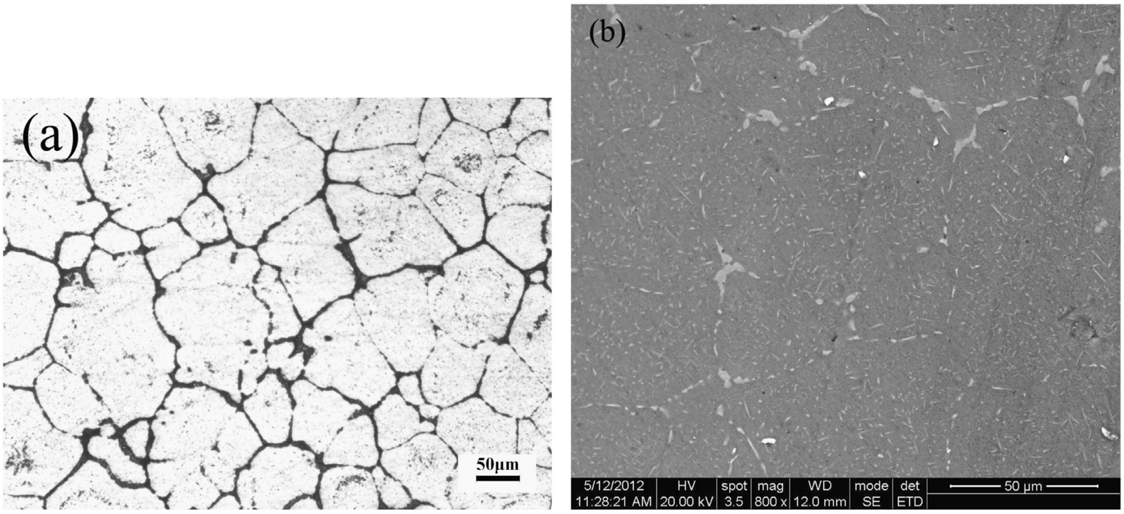

Fig. 1. Microstructure of as-received 7150 aluminum alloy: (a) OM; (b) SEM.