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Effect of Zr addition on hot deformation behavior and microstructural evolution of AA7150 aluminum alloy

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ABSTRACT

The hot deformation behavior of homogenized AA7150 aluminum alloys containing different Zr contents (0–0.19 wt%) was studied in uniaxial compression tests conducted at various temperatures (300–450 °C) and strain rates (0.001–10 s^{-1}). Microstructural evolution was investigated using an optical microscope, a field-emission gun scanning electron microscope, a transmission electron microscope and the electron backscattered diffraction technique. The results reveal no significant variation in the peak flow stress or activation energy between the 7150 base alloy and the alloy containing 0.04% Zr. With a further increase in the Zr content to 0.19%, the values of peak flow stress and activation energy increased significantly. The materials constants and activation energy for hot deformation were determined from the experimental compression data obtained for all alloys studied. The solved constitutive equations yielded good predictions of the peak flow stress over wide temperature and strain-rate ranges for 7150 alloys with different Zr contents. The dynamic recovery level of the materials was reduced after being alloyed with Zr, which was associated with a decrease in the mean misorientation angle of boundaries and a decrease in subgrain size. The addition of Zr promoted the retardation of dynamic recovery and the inhibition of dynamic recrystallization during hot deformation due to the pinning effect of Al_3Zr dispersoids on dislocation motion and to restrained dynamic restoration.

1. Introduction

7xxx series aluminum alloys are very attractive materials for their applications in the automotive and aerospace industries due to their excellent combination of properties such as high strength-to-density ratio, high fracture toughness and resistance to stress corrosion cracking [1]. These aluminum alloys are generally subjected to hot forming processes such as rolling, extrusion and forging. The mechanical properties of the alloys are affected by their chemical composition, strain history and resulting microstructure from thermomechanical processing [2,3]. The addition of micro-alloying elements, such as Zr, Sc, Sn, In, Cd and Ag, has also been reported to increase the material strength of the alloys and afford reasonably high toughness [4–7]. To optimize the mechanical properties and processability of hot formed alloys, a better understanding of the effect of micro-alloying elements on deformation behavior and microstructural evolution during hot deformation is required.

Dynamic recovery (DRV) and dynamic recrystallization (DRX) are the typical softening mechanisms active in aluminum alloys during deformation at elevated temperatures [8–11]. Previous investigations have shown that micro-alloying has significant effects on these softening mechanisms during hot deformation [12–15]. Hu et al. [12] suggested that the softening mechanism of 7050 aluminum alloy shifted from DRV to DRX with decreasing Z (Zener–Hollomon parameter). A minor addition of Sn (0.02–0.1%, all alloy compositions in wt% unless otherwise indicated) to Al–Cu–Mg alloy resulted in an increase in peak flow stress and deformation activation energy in a study reported by Banerjee et al. [13]. McQueen et al. investigated the hot torsion behavior of 8090 alloy containing 0.1% Zr and observed that dynamic recovery occurred as the sole softening mechanism [14]. However, dynamic recrystallized grains were observed in extruded Al–5% Mg–0.8% Mn alloy due to the stimulation of nucleation by Al_6Mn particles [15].

The addition of Zr is well known to increase the recrystallization resistance of aluminum alloys by forming fine, coherent Al_3Zr dispersoids [4,16]. The presence of these dispersoids promotes the formation of a stable and refined subgrain structure during the hot deformation process, which promotes additional substructure strengthening [17]. In commercial practice, Al_3Zr dispersoids are generally precipitated during the homogenization of cast billets [4,16]. The effectiveness of the dispersoids depends on their size, number density and distribution [18], which are strongly influenced by the homogenization treatment [19]. To date, several studies have focused on investigating the effect of Zr addition on

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the static recrystallization of aluminum alloys during solution treatment because the fracture toughness is closely related to the amount of recrystallized structure [4,16,20–22]. A few studies have been conducted on the hot deformation of aluminum alloys containing Zr, in which a pinning effect of Al_3Zr dispersoids on dislocations and grain boundaries has been reported [14,23,24]. However, a systematical investigation of the effect of different Zr contents on the hot deformation behavior of 7150 aluminum alloys has not been found in the literature. The evolution of the deformed microstructure of 7150 aluminum alloy after adding various contents of Zr must be understood.

In the present study, the hot deformation behavior of homogenized AA7150 alloys with different Zr contents (ranging from 0% to 0.19%) was studied by hot compression tests at various temperatures and strain rates. The constitutive equations correlating the peak flow stress, deformation temperature, strain rate and activation energy were analyzed for these alloys. The microstructural evolution of the alloys during hot deformation was investigated to understand the effect of Zr addition on the dynamic softening mechanisms that occur under various deformation conditions.

2. Experimental

Experiments were conducted on AA7150 alloys with different contents of added Zr ranging from 0% to 0.19%. The alloys were designated Alloy-A to Alloy-F based on their Zr contents, and their chemical compositions are presented in Table 1. Approximately 3 kg of material was melted in an electrical resistance furnace and then cast into a rectangular permanent steel mold measuring $30 \times 40 \times 80\ mm^3$. The cast ingots of these alloys were homogenized at 465 °C for 24 h, followed by direct water quenching. Cylindrical samples measuring 10 mm in diameter and 15 mm long were machined from the homogenized ingots. Uniaxial compression tests were conducted on a Gleeble 3800 thermo-mechanical simulation unit at strain rates of 0.001, 0.01, 0.1, 1 and $10\ s^{-1}$ and deformation temperatures of 300, 350, 400 and 450 °C, respectively. During the tests on the Gleeble 3800 unit, the samples were heated to the desirable deformation temperature at a heating rate of 10 °C/s and held for 3 min to ensure a homogeneous temperature distribution throughout the samples. The samples were deformed to a total true strain of 0.8 and then immediately water-quenched to retain the microstructure at the deformation temperature.

The microstructure of the as-homogenized materials was etched by Keller's solution prior to hot deformation. All deformed samples were sectioned parallel to the compression axis along the centerline and then metallographically prepared for electron backscattered diffraction (EBSD) analysis under a scanning electron microscope (SEM, JEOL JSM-6480LV). In EBSD analysis, the boundaries of both grains and subgrains are defined as low-angle boundaries (LABs), medium-angle boundaries (MABs) and high-angle boundaries (HABs) with misorientation angles of 1–5°, 5–15° and greater than 15°, respectively [25]. The step size between the scanning points was set to 1.0 μm for the grain structure of the samples. For the quantitative measurement of the misorientation distribution of boundaries, EBSD line scanning was carried out [26,27], and a sample surface area of approximately 2.73 mm^2 with a scanning step size of 1.0 μm was selected. In addition, EBSD analysis was performed to measure the subgrain size of the deformed samples using the linear intercept method [26]; a surface area of approximately 0.42 mm^2 with a scanning step size of 0.1 μm was selected. Samples for TEM observation were mechanically ground to a thicknesses of 35–60 μm and followed by electropolishing in a twin-jet polishing unit, which was operated at 15 V and −20 °C using a 30% nitric acid and 70% methanol solution. The samples were observed under a transmission electron microscope (TEM, JEM-2100) operated at 200 kV. To observe the distribution of Al_3Zr, electropolished TEM foils of an as-homogenized sample containing 0.12% Zr were examined using a field-emission gun SEM (Hitachi SU-70) operated at 10 kV with a working distance of 10 mm in the backscattered mode.

Table 1
Chemical composition of the alloys studied (wt%).

Alloy	Zn	Mg	Cu	Si	Fe	Ti	Zr	Al
Alloy-A (base alloy)	6.44	2.47	2.29	0.16	0.15	0.009	–	Bal.
Alloy-B (0.04 Zr)	6.27	2.14	2.23	0.11	0.14	0.008	0.04	Bal.
Alloy-C (0.07 Zr)	6.36	2.31	2.29	0.16	0.15	0.008	0.07	Bal.
Alloy-D (0.12 Zr)	6.35	2.22	2.34	0.16	0.15	0.008	0.12	Bal.
Alloy-E (0.15 Zr)	6.16	2.15	2.16	0.11	0.14	0.008	0.15	Bal.
Alloy-F (0.19 Zr)	6.04	2.08	1.97	0.11	0.14	0.008	0.19	Bal.

3. Results

3.1. Flow stress behavior

The hot compression tests of 7150 alloys containing different Zr contents were carried out at deformation temperatures ranging from 300 to 450 °C and at strain rates ranging from 0.001 to $10\ s^{-1}$. A series of typical true stress–true strain curves obtained during hot deformation are presented in Fig. 1. In general, all of the curves exhibit a peak flow stress at a certain strain, followed by dynamic flow softening to the end of straining. Significant flow softening beyond the peak stress was observed at the highest strain rate of $10\ s^{-1}$, which was attributed to severe adiabatic deformation heating. This phenomenon was reported in our previous study [28], in which the deformation temperature considerably rose during the compression process. Under other deformation conditions, the flow stress curves remained fairly constant or decreased to some extent beyond the peak stresses, demonstrating a dynamic equilibrium between work hardening and dynamic softening. In addition, it is evident that the level of flow stress and peak stress increased with increasing strain rate and decreasing deformation temperature, which is in general agreement with the results reported in previous studies on metallic alloys [12–15,23,24]. However, the flow stress and peak stress levels increased remarkably with an increase in Zr content.

Fig. 2 illustrates the evolution of the peak flow stresses of the alloys with different Zr contents as a function of strain rate at various deformation temperatures. Under a given deformation condition, no significant variation could be observed in the peak stress between the base alloy (Alloy-A) and Alloy-B with 0.04% Zr. With the further addition of Zr, increasing the content from 0.07% to 0.19%, the peak stress levels increased significantly. The values of peak stress showed a gradual rise with increasing content of Zr under the same deformation condition. For example, when hot deformation was performed at 300 °C and $0.1\ s^{-1}$, the peak stress of the base alloy was 130.4 MPa, which increased to 136.3 MPa and 139.7 MPa after the material was alloyed with 0.12% and 0.19% Zr, respectively. As the deformation temperature increased to 450 °C at the same strain rate of $0.1\ s^{-1}$, the peak stresses of the alloys containing 0.12% and 0.19% Zr increased to 55.68 MPa and 59.22 MPa, representing 6.2% and 13% increases, respectively, relative to the peak stress in the base alloy. The results indicate that micro-alloying with a Zr content greater than 0.04% could remarkably retard the dynamic softening of the base material and enhance its deformation resistance during deformation at elevated temperatures.