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Hot deformation behavior of homogenized Al−3.2Mg−0.4Er aluminum alloy

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Abstract: The hot deformation behavior of the homogenized Al−3.2Mg−0.4Er aluminum alloy was investigated at 573−723 K under strain rates of 0.001−1 s^{-1}. On the basis of compression experimental results, an accurate phenomenological constitutive equation that coupled the effects of strain rate, deformation temperature and strain was modeled. Furthermore, a kinetic model of dynamic recrystallization and processing map were also presented. The results show that the flow stress of the studied Al−3.2Mg−0.4Er alloy can be predicted accurately using the proposed constitutive model. The evolution of microstructure and the volume fraction of dynamic recrystallization can be described exactly in terms of S-curves with the proposed kinetic model. Moreover, the processing maps for hot working at different strains were constructed, suggesting the optimum processing conditions for this alloy are 573 K, 0.001 s^{-1} and 723 K, 0.001−0.1 s^{-1}.

Key words: Al−Mg alloy; hot deformation; constitutive model; processing map

1 Introduction

The Al−Mg series alloys are widely used in aerospace and vehicle industries owing to their good combined properties, such as medium strength, high ductility, excellent corrosion resistance, and welding ability [1]. Demand for alloys with further reduced mass and thickness, high efficiency, good mechanical properties and corrosion resistance, has recently increased. To meet these requirements, efforts have been expended to improve the workability and mechanical properties of these alloys. Recent studies have shown that adding small amount of Er could significantly improve the thermal stability, increase the strength, and refine the grain structure of Al−Mg alloys [2−4]. GAO et al [5] reported that the addition of 0.2% Er (mass fraction) can refine dendritic structure and change the morphology and size of Fe-phase of aluminum alloys. Moreover, the nanoscaled Al_3Er phase formed during aging process can improve the strength and recrystallization resistance. WU et al [6] found that during hot deformation, the constituents with Er and Mg fracture first and act as the microcrack sources due to the stress concentration and then the solution treatment after thermomechanical process is a fundamental procedure to improve the mechanical properties of the Al−Mg alloys by the addition of Er element. Furthermore, Er can be added into the Al-based alloys as an attractant to improve the precipitation hardening response and the thermal stability, such as Al−Zr [7]. All of these beneficial effects of Er are attributed to the formation of nanoscaled Al_3Er phase, which is L12 structure and coherent or semi-coherent with Al matrix. Given the rapid cooling rate during conventional DC casting, most of the Er atoms dissolve in the Al matrix, resulting in a supersaturated solid solution that decomposes via precipitation of dispersed particles during homogenization prior to hot rolling or extrusion [8].

The information on hot deformation parameters of homogenized Al−3.2Mg−0.4Er alloy is scarce, thereby limiting the applications of the Al−3.2Mg−0.4Er alloy. Therefore, this study aimed to characterize the high temperature deformation behavior of the homogenized Al−3.2Mg−0.4Er alloy through the hot compression experiment. Several modeling approaches, including

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flow stress−strain curves, phenomenological constitutive model, kinetic model of DRX and processing map, were used to characterize the deformation behavior of the homogenized Al−3.2Mg−0.4Er alloy.

2 Experimental

Cylindrical specimens (*d*8 mm × 12 mm) were machined from the Al−3.2Mg−0.4Er alloy ingot, and the chemical composition of the studied alloy is shown in Table 1. The alloy was then homogenized at 723 K for 12 h. The hot compression corresponding to a 60% height reduction was performed on a Gleeble thermo-mechanical simulator at 573−723 K in a strain rate range of 0.001−1 s^{-1}. The specimens were heated at a heating rate of 5 K/s and then held at a certain temperature for 5 min. The specimens were compressed to a true strain of 0.9 and then quenched in water immediately to maintain the deformed microstructure. For microstructure observation, all the specimens were sectioned parallel to the longitudinal compression axis. The microstructure was characterized by electro-polishing the specimens using a solution consisting of 10% perchloric acid and 90% methanol and observing them under an optical microscope.

Table 1 Chemical composition of Al−3.2Mg−0.4Er alloy (mass fraction, %)

Mg	Er	Zn	Fe	Si	Al
3.18	0.4	0.19	0.04	0.03	Bal.

3 Results and discussion

3.1 Flow stress analysis

Figure 1 shows the microstructure of the Al−3.2Mg−0.4Er alloy homogenized at 723 K for 12 h. The average grain size of this alloy after the homogenization heat treatment is approximately 359 μm. The hot deformation behavior of the homogenized Al−3.2Mg−0.4Er alloy was studied by hot compression in a strain rate range of 0.001 s^{-1}−1 s^{-1} at 573−723 K. Figure 2 shows typical true stress−strain curves obtained during hot compression of Al−3.2Mg−0.4Er alloy. The flow stress is generally sensitive to strain rate and deformation temperature. The decrease in strain rate and increase in temperature indicate a significant decrease in flow stress. The work hardening at the beginning of hot compression results in the rapid increase of flow stress. Moreover, with the increase in strain, dislocation density and potential driving force or recovery increase. Meanwhile, nucleation and growth of new grains occur. Additionally, an obvious feature of the flow curves is the lack of clear evidence of DRX which is usually identified by a distinct peak [9]. However, to clarify the occurrence of dynamic recrystallization, some precise tests on the microstructure of the deformed specimens should be carried out.

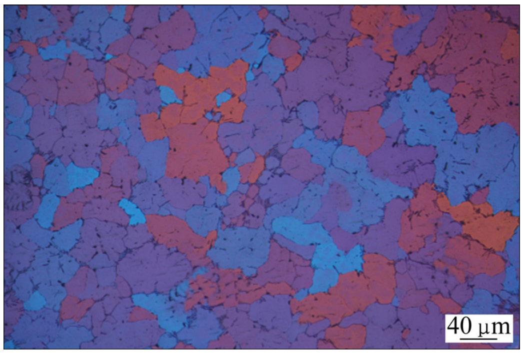

Fig. 1 Microstructure of Al−3.2Mg−0.4Er alloy homogenized at 723 K for 12 h

Figure 3 shows the effect of deformation parameters on peak stress of the Al−3.2Mg−0.4Er alloy. The peak stress decreases with increasing deformation temperature and decreasing strain rate. Moreover, the decreasing rate of peak stress decreases with decreasing strain rate from 1 to 0.001 s^{-1} at low temperatures, whereas peak stress decreases smoothly at high temperatures of 673 and 723 K.

3.2 Constitutive equation

In order to improve the prediction accuracy of the flow stress of the Al−3.2Mg−0.4Er alloy, a phenomenological constitutive model, which considers the coupled effects of strain rate, strain and deformation temperature on the flow behavior of material, is presented [10]. This phenomenological constitutive model can be expressed as follows:

$$\sigma = [\sigma_p + B(T)\varepsilon^{n(T)}][1 + C(T,\varepsilon)\ln(\dot{\varepsilon}/\dot{\varepsilon}_0)] \tag{1}$$

where $B(T)$ and $n(T)$ are material constants, which are functions of forming temperature; material constant $C(T,\varepsilon)$ represents the effects of strain and deformation temperature on the flow behavior of material; σ_p is the peak stress under different deformation conditions.

3.2.1 Determination of σ_p

The Arrhenius equation, which gives better approximations between Zener−Hollomo parameter and flow stress, is widely accepted to describe the hot deformation behavior of alloys [11]. This theory can be expressed as follows:

$$Z = \dot{\varepsilon}\exp[Q/(RT)] \tag{2}$$

$$\dot{\varepsilon} = AF(\sigma)\exp[-Q/(RT)] \tag{3}$$