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Hot deformation and processing maps of an Al–5.7 wt.%Mg alloy with erbium

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ABSTRACT

The hot deformation behavior of an Al–5.7 wt.%Mg alloy with erbium has been investigated. Compression tests are performed in the temperature range of 300–500 °C and in the strain rate ranging from 0.001 s^{-1} to 50 s^{-1} up to a true strain of 0.7. The processing maps are developed at different strains and the standard kinetic analysis has been applied to evaluate the rate controlling mechanisms. The processing maps have exhibited two domains of 350–450 °C at 0.001–0.03 s^{-1} and 450–500 °C at 0.01–1 s^{-1}, representing dynamic recovery of Al–5.7 wt.%Mg with erbium. The apparent activation energies estimated in these two domains are 180 kJ/mol and 163 kJ/mol respectively, which suggests that cross-slip of dislocation and lattice self-diffusion are the deformation mechanisms. At strain rates higher than 10 s^{-1}, the flow curves demonstrate flow softening behavior, and the flow instability regions reveal mixed microstructure of local deformation and dynamic recrystallization.

1. Introduction

Al–Mg alloys have a great potential for aircraft and automotive body sheet applications due to its excellent combination of strength, corrosion resistance and weldability. It has been found the addition of erbium in Al–Mg alloys can effectively increase the recrystallization temperature with the coherent nanoscale Al_3Er dispersions formed during cooling after solidification [1,2], which will affect the hot working behavior of Al–Mg alloys. Different approaches are available for evaluating the working mechanisms and these include evaluation of the stress–strain curves and the standard parameters such as stress exponent or activation energy. Much studies were put on the flow curves and constitutive equations [3–6] in the past and a promising approach—processing maps based on Dynamic Materials Model has been developed [7–11], with the purpose of optimizing hot working process and controlling microstructure.

Dynamic Materials Model is applicable to the materials undergoing hot working process characterized by dynamic, nonlinear and irreversible phenomena [12]. The model considers the work piece to be a dissipater of power and the power might be instantaneously dissipated into two complementary parts—G content and J co-content:

$$P = \bar{\sigma} \cdot \dot{\bar{\varepsilon}} = G + J = \int_0^{\dot{\bar{\varepsilon}}} \bar{\sigma} \cdot \mathrm{d}\dot{\bar{\varepsilon}} + \int_0^{\bar{\sigma}} \dot{\bar{\varepsilon}}\ \mathrm{d}\bar{\sigma} \quad (1)$$

where G represents the power dissipated by plastic work, most of which is converted into viscoplastic heat, the little remaining power is stored as lattice defects. The co-content J is related to the power dissipated by metallurgical processes, such as recovery, recrystallization, phase transformation, wedge cracking, etc. [13–18]. The total input power is partitioned between these two parts by the strain rate sensitivity of flow stress, i.e. m [7]:

$$\frac{\mathrm{d}J}{\mathrm{d}G} = \frac{\dot{\bar{\varepsilon}}\ \mathrm{d}\bar{\sigma}}{\bar{\sigma}\ \mathrm{d}\dot{\bar{\varepsilon}}} = \frac{\mathrm{d}(\ln\bar{\sigma})}{\mathrm{d}(\ln\dot{\bar{\varepsilon}})} \approx \frac{\Delta\ \log\bar{\sigma}}{\Delta\ \log\dot{\bar{\varepsilon}}} = m \quad (2)$$

For an ideal linear dissipater, J reaches its maximum $J_{\max}$ when $m = 1$, which is $J_{\max} = \bar{\sigma} \cdot \dot{\bar{\varepsilon}}/2$. The dimensionless parameter, efficiency of power dissipation η is defined as [19]

$$\eta = \frac{J}{J_{\max}} = 2\left(1 - \frac{1}{\bar{\sigma} \cdot \dot{\bar{\varepsilon}}} \int_0^{\dot{\bar{\varepsilon}}} \bar{\sigma} \cdot \mathrm{d}\dot{\bar{\varepsilon}}\right) \quad (3)$$

Which could represents the character of power dissipation in the work piece. From the variation of η with temperature and strain rate the power dissipation maps can be constructed. The various domains in the maps may be correlated with specific microstructure processes. The hot deformation mechanisms are dynamic recovery, dynamic recrystallization and superplasticity, which are safety hot deformation process, while wedge cracking, adiabatic shear, flow localization, etc., are damage processes. Different instability criterion has been formulated to identify the regions of flow instabilities [20–22], by which the instability maps are also constructed. A superposition of power dissipation map on the instability map constitutes a processing map, which could be used for characterizing different domains where individual microstructural

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process occurs and for limiting conditions in the regions of flow instability.

Prasad has developed a criterion for evaluating the regions of flow instabilities by assuming the power law nature of stress distribution [8]

$$\bar{\sigma} = K\bar{\dot{\varepsilon}}^{m} \tag{4}$$

The efficiency of power dissipation η can be expressed as

$$\eta = \frac{2m}{m+1} \tag{5}$$

And the condition for instability can be obtained [9]

$$\xi(\bar{\dot{\varepsilon}}) = \frac{\partial \ln(m/(m+1))}{\partial \ln \bar{\dot{\varepsilon}}} + m < 0 \tag{6}$$

where $\xi(\bar{\dot{\varepsilon}})$ is a dimensionless instability parameter, and the variation of $\xi(\bar{\dot{\varepsilon}})$ with temperature and strain rate constitutes an instability map. In this map, the regions where $\xi(\bar{\dot{\varepsilon}})$ is negative represent microstructure instabilities. This criterion is widely used and has been confirmed correct for many alloys [11–17]. However, Narayana Murty et al. consider that the efficiency of power dissipation (η) given in Eq. (5) in terms of the strain rate sensitivity parameter (m) is only valid explicitly when the flow stress–strain rate curve obeys power law [23–25], where m is independent on strain rate. Otherwise, if the m is dependent on strain rate, then Eq. (6) becomes erroneous. So they propose a simplified flow instability condition for any type of flow curves [19]

$$2m < \eta \ \text{or}\ m < 0 \tag{7}$$

The instability region identified by Eq. (7) is larger than that identified by Eq. (6), which is consistent with the experiment results. The same conclusion is also obtained in other alloys and the criterion should be more appropriate for delineating the regions of unstable metal flow during hot deformation.

Instability criterion proposed by Prasad is based on the assumption that flow stress obeys the power law and the strain rate sensitivity m is constant. However, flow instabilities are easily occurred during hot working at high strain rate, which reduces the flow stress, and the strain rate sensitivity m may get a negative value, leading to the criterion Eq. (6) becoming erroneous. The criterion derived by Narayana Murty is based on the continuum principles applied to large plastic flow, with no such restriction that it may be more promising approach to identify the unsafe regions in the processing maps. The validity of processing maps has been approved in many alloys but little report is found on aluminum alloys with erbium. Dynamic recrystallization usually occurs at these regimes with peak efficiency. However, aluminum alloys have high stacking fault energy and recrystallization is not easy taking place during hot working. This investigation is therefore to study the hot deformation characteristics of Al–5.7 wt.%Mg alloy with erbium with the help of processing maps combined with flow curves and kinetic analysis. The influence of erbium on the compression behavior of Al–5.7 wt.%Mg alloy is also discussed.

2. Experimental procedure

The alloy used in this investigation was made by electromagnetic stirring casting, and the chemical composition (wt.%) is listed in Table 1. The cast was homogenized for 13 h at 470 °C. Cylindrical specimens with 10 mm in diameter and 15 mm in height were machined from the homogenized materials for compression. Hot compression tests were conducted in the temperature range of 300–500 °C at 50 °C intervals and constant true strain rate ranging from 0.001 to 50 s^{-1} at intervals of an order of magnitude. The specimens were padded with slices of graphite to reduce the friction during compression. Before compression, specimens were heated to test temperature and held for 5 min for equilibration. The

Table 1
Chemical composition (wt.%) of the alloy used in the present study.

Mg	Mn	Zr	Er	Al
5.7	0.73	0.13	0.33	Remainder

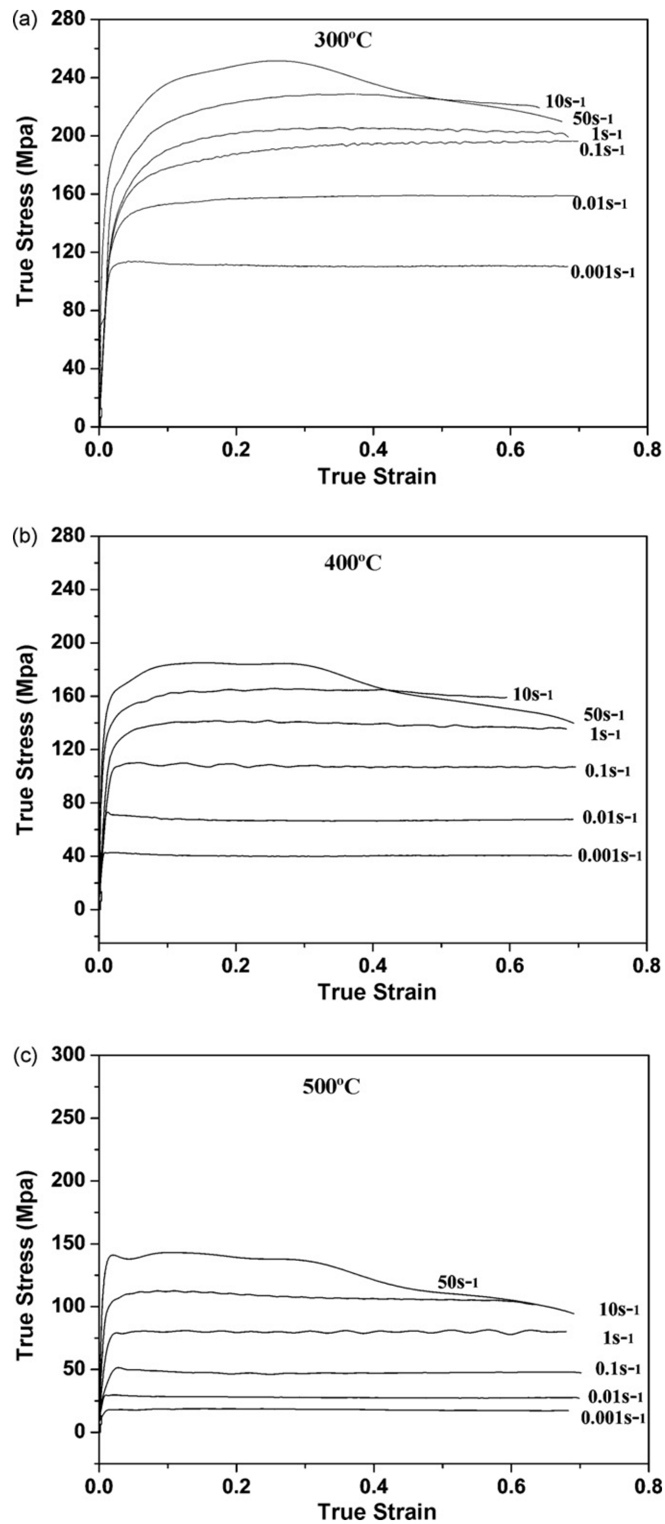

Fig. 1. True stress–true strain curves obtained in compression on Al–5.7 wt.%Mg alloy with erbium at (a) 300 °C; (b) 400 °C and (c) 500 °C for various strain rates.