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Flow stress and microstructural evolution of the horizontal continuous casting Al–0.96Mn–0.38Si–0.18Fe alloy during hot compression

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ABSTRACT

Hot compression tests of the horizontal continuous casting Al–0.96Mn–0.38Si–0.18Fe alloy were preformed on Gleeble-1500 system in the temperature range from 350 °C to 500 °C and at strain rate range from 0.01 s^{-1} to 10 s^{-1}, and the associated microstructural changes were studied by the observations of optical metallographic and transmission electron microscope. The results show that the flow stress below 450 °C and at higher strain rates increases with increasing strain and tends to be constant after a peak value, showing a steady state flow until high strains. While above 450 °C and at lower strain rates, the flow stress reaches a plateau and then decline slightly, showing a flow softening. The peak stress level decreases with increasing deformation temperature and decreasing strain rate, which can be represented by a Zener–Hollomon parameter in the hyperbolic-sine equation with the hot deformation activation energy of 159.24 kJ/mol. The steady state flow results from dynamic recovery whereas flow softening is associated with dynamic recrystallization and dynamic transformation of precipitates. The designed columnar coarse grains were capable of GDRX above 450 °C and at lower strain rates.

1. Introduction

The growing demand for more fuel-efficient vehicles to reduce energy consumption and air pollution is a challenge for the automotive industry. The characteristic properties of aluminum, high strength stiffness to weight ratio, good formability, good corrosion resistance, and recycling potential make it the ideal candidate to replace heavier materials (steel or copper) in the car to respond to the weight reduction demand within the automotive industry. One of the increasing applications of Al alloys in vehicles is heat exchangers (with tube and fin components) such as radiators, evaporators, engine cooling and air conditioning systems [1–3]. The 3000 series alloys, based on the Al–Mn system, are processed into sheet and extruded products which are widely used for heat exchangers due to the combination of strength, formability, brazeability, and corrosion resistance. The standard commercial Al alloy for heat exchanger applications is AA3003 alloy containing about 1 wt% Mn. This grade of Al alloy provides good formability, mechanical strength and acceptable corrosion performance. In addition, developing alloys based on the AA3003 composition have improved the corrosion resistance and mechanical performance to meet the challenge of the reduction in thickness of tube and fin materials in automotive heat exchanger applications in the future.

Hot deformation is a key manufacturing process for Al–Mn alloys. Therefore, designing and developing new tube and sheet alloys with improved properties require a detailed understanding of the hot deformation mechanisms of these alloys. Early research has indicated that the flow curves of the Al–1Mn alloy reached a steady state with higher ductilities in torsion deformation at higher temperatures and the temperature and strain rate dependencies of the peak stress were fitted to a sinh-Arrhenius equation with hot deformation activation energy of 152 kJ/mol. The softening results from dynamic recovery which above 400 °C gives rise to elongated grains with serrated boundaries and larger subgrains at lower strain rate [4]. Nes [5,6] reported some preliminary results on the structural stability of a Zr-bearing Al–Mn alloy (Al–0.9Mn–0.4Zr) during hot deformation. During hot-deformation the subgrain size increased while the density of Al_3Zr particles decreased with increasing strain. The decrease in particle density was caused by a discontinuous dissolution reaction at migrating sub-boundaries. This dissolution resulted in a subsequent reprecipitation of Al_3Zr particles (the metastable phase). The strain-induced subgrain growth process has been classified as a continuous recrystallization reaction.

Typically, the weight percent of Fe is higher than that of Si in order to reduce cracks of casting ingots in 3000 series alloys. And the alloy additions of Mn, Fe, Si will retard recrystallization [7,8].

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In the present study, the hot compression tests of the horizontal continuous casting Al–0.96Mn–0.38Si–0.18Fe alloy are to be preformed on Gleeble-1500 machine at strain rate ranged between 0.01–10 s^{-1} and deformation temperature of 350–500 °C. The purpose of this is to gain a fundamental understanding of the hot deformation behavior of this alloy, including the effects of thermo-mechanical parameters on the flow stress and microstructural changes.

2. Experimental procedure

The experiments were carried out on an Al–0.96Mn–0.38Si–0.18Fe alloy. The initial optical microstructures with columnar coarse grains of the studied horizontal continuous casting alloy are shown in Fig. 1. Cylindrical samples with 10 mm in diameter and 15 mm in height were machined from commercially horizontal continuous casting stock with 12 mm in diameter. Convex depressions 0.2 mm deep were machined on both ends of the samples in order to maintain the lubricant of graphite mixed with machine oil during compression tests. Isothermal compression tests were carried out on a computer servo-controlled Gleeble-1500 system at strain rates of 0.01–10 s^{-1} and deformation temperature of 350–500 °C, with the specific true strains of 0.8. The sample was resistance heated to deformation temperature at a heating rate of 10 °C/s and held at that temperature for 180 s by thermo-coupled-feedback-controlled AC current before compression, the samples were deformed to half of their original height and water quenched immediately. The deformed microstructures were sectioned parallel to the compression axis along the direction of centerline and prepared by the conventional methods for the microstructural observations on the MM-6 metallographic microscope (OM) after etching by 50% HF enchants for 30 s. The thin samples were examined on the JEM3010 transmission electron microscope (TEM) after electropolishing in a solution of 30% HNO_3 and 70% methanol at 25 V and at −30 °C.

3. Results and discussion

3.1. Flow stress

Fig. 2 shows the true stress–true strain curves of the Al–0.96Mn–0.38Si–0.18Fe alloy deformed at strain rates of 0.01–10 s^{-1} and temperature of 350–500 °C. It can be seen that significant effects of deformation parameters (strain, temperature and strain rate) on the flow stress are presented. The flow stress increases with increasing strain and tends to be constant after a peak value, showing a steady state flow until the end of compression under deformation temperature below 400 °C and at higher strain rates. But when deformed above 400 °C and at lower strain rates, the flow stress reach a plateau and then decline slightly until high strains, showing a flow softening which has been observed in several series aluminum alloys [9–11]. The peak stress values increase with increasing strain rate and decreasing deformation temperature. And because of the difference of high hardening rate at initial deformation stages, the strain corresponding to the peak stress increases with increasing strain rate and with decreasing deformation temperature. The flow behavior is probably subjected to the dynamic recovery and dynamic recrystallization during hot deformation of the non-heat-treatable aluminum alloys [4,12–14]. The actual hot deformation mechanisms for the studied alloy will be discussed in detail in the following section by comparison analysis with hot deformation activation energy calculation and microstructural observation.

3.2. Constitutive equations

In hot deformation of aluminum alloys, the constitutive equations are developed to model the hot deformation behavior of the materials and to demonstrate the effects of deformation conditions on the state of flow stress. In general, the following constitutive equations are applied in hot deformation [15–17]:

$$Z = f_1(\sigma) = A_1\sigma^{n_1} \tag{1}$$

$$Z = f_2(\sigma) = A_2\exp(\beta\sigma) \tag{2}$$

where A_1, A_2, n_1 and β are constants, σ is the peak stress or steady state stress (MPa), Z is the Zener–Hollomon parameter that can be expressed as:

$$Z = \dot{\varepsilon}\exp\left(\frac{Q}{RT}\right) \tag{3}$$

where $\dot{\varepsilon}$ is the strain rate (s^{-1}), T is the deformation temperature (K), Q is an activation energy for hot deformation (J/mol) and R is the gas constant (8.314 J/mol/K). The power law, Eq. (1), and the exponent-type equation, Eq. (2), break at a high stress and at a low stress, respectively. The hyperbolic sine type equation (Eq. (4)), proposed by Sellars and McTegart [18], is a more suitable equation for stresses over a wide range.

$$Z = f(\sigma) = A(\sinh\alpha\sigma)^n \tag{4}$$

where A and n are constants. α is the stress multiplier, also the additional adjustable parameter and

$$\alpha = \frac{\beta}{n} \approx \frac{\beta}{n_1} \tag{5}$$

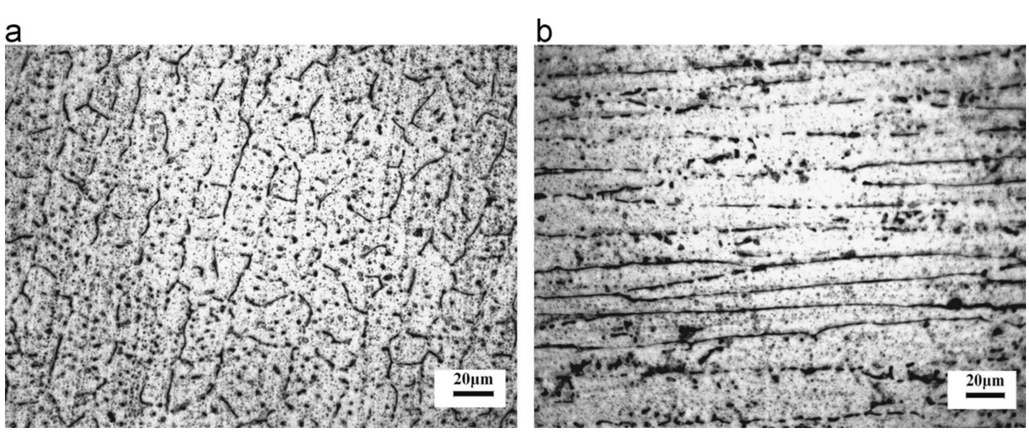

Fig. 1. Optical microstructures of the horizontal continuous casting Al–0.96Mn–0.38Si–0.18Fe alloy: (a) transverse section; (b) longitudinal section.