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Modeling the microstructure evolution in AZ31 magnesium alloys during hot rolling

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ABSTRACT

A new model was proposed based on the dislocation density of the computer simulation of the microstructure evolution in magnesium alloys. It is possible to describe the continuous dynamic recrystallization (CDRX) interaction including work-hardening, dynamic recrystallization (DRX) and dynamic recovery (DRV) changing with rolling time. The transient hot rolling simulation was performed by implementing this model under various rolling temperatures and strain conditions using the finite diffraction method (FDM). Normal rolling experiments were conducted at different reductions and starting rolling temperatures. Microstructural parameters, such as grain size, subgrain size, misorientation angle, high-angle grain boundary (HAGB), and low-angle grain boundary (LAGB), were measured using electron back-scattering diffraction (EBSD). The dislocation density of LAGB and the hypothetical dislocation density of HAGB were estimated through theoretical derivation using the experimental data. As a result, changes in the hypothetical dislocation density of HAGB and the dislocation density of LAGB of the model prediction fit well with the experimental data. The microstructure evolution mechanisms of the AZ31 magnesium alloy in the roll bite were examined at 300, 400 and 500 °C rolling. As a result, it is clear that the work-hardening is a dominated mechanism of 300 °C rolling in the rolling strain ranging from 0 to 0.6. However, the DRV plays a vital role in the microstructure evolution at 400 and 500 °C rolling.

1. Introduction

The research on and development of magnesium sheets by rolling have been greatly expanded in the last years, particularly for the purpose of weight reduction, energy saving, and environmental protection. Controlling the evolved microstructure during rolling is critical because of its direct effect on the final properties of the sheet product. One method of achieving this control is based on direct experimental investigations. Another method is based on physically based mathematical models that predict the microstructure evolution and therefore reflect the influence of the process parameters on the final microstructure.

Many studies have analyzed the microstructure evolution in magnesium alloys during hot deformation and its related mechanisms. Ion et al. (1982) investigated DRX in extruded magnesium compressed parallel to the basal planes at the temperature range of 423 K–593 K. The DRX mechanism was proposed to consist of twinning, basal slip, and lattice rotations at grain boundaries. This DRX process is termed rotational recrystallization. Myshlyaev et al. (2002) analyzed the DRX mechanisms of the AZ31 alloy at a temperature range of 453 K–723 K using hot torsion tests. A climb process with an activation energy of 140 KJ/mol is close to this range for self-diffusion. They consequently emphasized the role of DRV in forming substructure and microstructure heterogeneities. Koike et al. (2003) confirmed that DRV can occur in Mg alloys at room temperature by tensile tests. Humphreys and Hatherly (2004) claimed that minimal boundary migration occurs during the DRX process and no clear division can be established between nucleation and growth. This mechanism was therefore categorized under the group of continuous recrystallization (CDRX) mechanisms. Yang et al. (2009) studied grain refinement mechanism in AZ31 magnesium alloys using multi-directional forging at a temperature range of 423 K–623 K. The development of kink bands was found during the formation of new grains. Therefore, the DRX mechanism was classified as CDRX as well. These reviews show that the DRX mechanisms of AZ31 magnesium alloys are generally controlled by CDRX.

The restoration mechanism operated in CDRX is principally DRV, which occurs in materials of high stacking fault energy (SFE). These materials include aluminum, aluminum alloys, and ferritic steels. Myshlyaev et al. (2002) reported the SFE of magnesium is 135 KJ/mol, which is of similar magnitude to other high-SFE metals. However, only

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minimal attention has been given to the microstructural modeling of high-SFE metals that undergo CDRX during hot deformation. Although the modeling techniques of microstructure evolution have undergone great progress in the last decade, a suitable model based on the physical parameters of dislocation density remains lacking to describe the complex CDRX interaction in magnesium alloys during hot rolling.

The Johnson–Mehl–Avrami–Kolmogorov (JMAK) equation based on classical theory is traditionally used to describe the recrystallization of aluminum alloys and steels for isothermal phase transformation kinetics. Raghunathan and Sheppard (1989) and Duan and Sheppard (2002) calculated the recrystallised volume fraction and the grain size of aluminium alloy AA5083 used a commercial finite element method (FEM) program combined with empirical models. Numerous works have used the FEM in combination with the JMAK equation. The models are not repeated here. This empirical model provides a useful tool of quantitatively examining the effect of deformation conditions on the microstructure evolution in the material. However, the great number of material constants and relatively simplistic methods of representing the deformation history undergone by the material limit the applicability of the model.

Electron backscatter diffraction (EBSD) is an important tool of investigating CDRX, and considerable attention has been given to the development of physically based state variable models. Parameters, such as dislocation density, subgrain size, and misorientation, are considered by the model in predicting microstructure evolution during hot deformation. Lyttle and Wert (1994) developed a new models to explain changes in HAGB% and microstructure evolution in various aluminum materials during hot working. The results show that misorientations are mainly increased by grain boundary sliding and subgrain switching. However, the two mechanisms above are typical of the superplastic mechanisms; they are restricted by their very low strain rates and are therefore not suitable for thermo-mechanical processing conditions.

Luce et al. (2001) proposed a dislocation model which included three types of dislocation densities to describe not only work-hardening but also the dynamic and static recovery of Al alloy (AA3004). Ahmed et al. (2005) investigated microstructure evolution during and after the hot rolling of AA5083 using an internal state variable approach in a FE model. The model was able to predict the fraction of DRX and the recrystallized grain size under industrially relevant hot deformation conditions. Sellars and Zhu, 1998 and Sellars and Zhu (2000) established a microstructural model based on the classical theory of work-hardening and DRV, as given by the following equation:

$$d\rho_r = d\rho_r^+ + d\rho_r^- = (c_1\rho_r^{1/2} - c_2\frac{\sigma_f}{Z}\rho_r)d\varepsilon \quad (1)$$

where ρ_r is the random dislocation density, c_1 and c_2 are material-based constants, Z is the Zener–Hollomon parameter, σ_f is the frictional stress, and $d\varepsilon$ is an increment of deformation strain.

Gourdet and Montheillet (2002) and Gourdet and Montheillet (2003) also published a model of CDRX. In the model, strain hardening and DRV can be described by the Laasraoui and Jonas (1991) equation:

$$d\rho_i = (h - r\rho_i)d\varepsilon - \rho_i dv \quad (2)$$

$$h = h_0\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^m \exp(\frac{mQ}{RT}) \quad (3)$$

$$r = r_0\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{-m} \exp(\frac{-mQ}{RT}) \quad (4)$$

where h and r denote the strain hardening and dynamic recovery parameters, and dv is the volume swept by the mobile boundaries. A dislocation density $d\rho_i^+ = hd\varepsilon$ is produced by the deformation, whereas $d\rho_i^-(1) = r\rho_i d\varepsilon$ is removed from ρ_i by either "condensation" into new LAGBs or absorption into the pre-existing boundaries. The predictions of the model were presented for both the transient and steady states, including stress–strain curves at various temperatures and strain rates, and the associated evolutions of the microstructure parameters, such as crystallite size, dislocation density, and LAGB misorientation distribution. However, their studies were not validated by quantitative comparison with experimental results.

The foregoing literature review indicates that the DRX behavior of magnesium alloy is characterized as the CDRX. However, the DRX mechanisms in magnesium and its alloys differ under various temperatures and strain conditions because of their HCP crystal structure; thus, different slip systems are operated under various deformation temperatures. The microstructure evolution in magnesium alloys during hot rolling is difficult to model because the internal structure evolves with rolling time through the interaction of mechanisms, such as work-hardening, DRV, and DRX. The work proposes a mathematic model based on the dislocation density that is appropriate to simulating the microstructure evolution in magnesium alloy during hot rolling. The model in this work is validated through the microstructural measurement of rolling sheets under different rolling conditions using EBSD. The mechanisms and factors (DRV and work-hardening) that influence the microstructure evolution in AZ31 magnesium alloys during hot rolling are discussed by adjusting some of the parameters of the model.

2. Experimental procedure

The magnesium alloys used in the present study consisted of hot rolled alloys made from commercially available Mg–Al–Zn (AZ31B-O) sheets with a thickness of 10 mm. Before the deformation experiments, the received sheet was hot rolled at 400 °C in four passes and then cooled in air. After annealing at 450 °C for 30 min, the starting sheets with a thickness of 5.6 mm, width of 40 mm, and length of 150 mm had a fully recrystallized microstructure with a mean grain size of 26.4 μm. The sheets were held for 30 min in an electric furnace at 300, 350, 400, 450, and 500 °C. Normal rolling was then conducted at reduction rates of approximately 20%, 30%, 35%, and 40% in one pass at a constant rolling speed of 246 mm s^{-1}. A 2-high rolling mill with a diameter of 200 mm was used without lubrication. Both rolls were stored at room temperature. The rolled sheets were cooled in ice water to freeze the microstructure for measurements within 2 s after rolling. Guo and Fujita (2012) has reported the method of EBSD analysis.

3. Thermal–mechanical analysis during hot rolling

The method of the embedded pin in the rolling sheet was adopted as stated in previous studies by Guo and Fujita (2012). Fig. 1 presents the FDM model of the work roll and Mg sheet. The thermal–mechanical analysis during hot rolling in the roll bite was performed by FDM using a Visual Basic for application (VBA) program by Guo and Fujita (2015). The temperature and strain distributions in the roll bite during hot rolling were obtained from the thermal–mechanical analysis. The

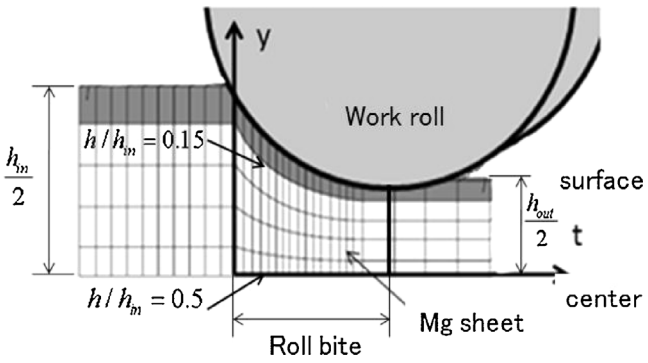

Fig. 1. FDM model of the work roll and Mg sheet. Guo and Fujita (2012).