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The flow stress evolution and grain refinement mechanisms during hot deformation of Al-Mg alloy

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Abstract

In this study, the hot deformation behavior of an Al-1% Mg alloy with very coarse initial grain size was investigated in terms of flow stress evolution and grain refinement mechanism. The large grain size was employed to study the traditional continuous dynamic recrystallization (CDRX) behavior below the critical strain to reach classical geometric dynamic recrystallization (GDRX), i.e., the thickness between HAGBs decreases and impingement of serrated HAGBs finally leads to the formation of new grains. The microstructure evolution during hot deformation with different deformation temperatures and strain rates on Gleeble 3800 machine was examined systematically by EBSD. It is concluded that, among the investigated conditions, the stress increases with strain and could reach steady state at small strain of ~0.01 at higher deformation temperature, while it keeps increasing at lower deformation temperature. The grain refinement mechanism clearly depends on the hot deformation condition, (micro)shear band assisted grain refinement was observed at lower deformation temperature and CDRX dominated at high deformation temperatures. In the conditions favoring CDRX, the grain refinement process is strongly grain orientation dependent, there exist some stable orientations inside which the formation of subgrain boundaries are difficult. The connection between the stress-strain behavior and microstructural evolution during hot deformation is further discussed. As compared to the traditional CDRX mechanism, the results presented in this paper provide a clearer and more complete picture of the grain refinement mechanism during hot deformation of Al-Mg alloys.

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Keywords: Aluminium alloy; Grain refinement; Hot deformation; Dynamic recrystallization

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1. Introduction

It is known that grain refinement, which usually leads to improved mechanical properties, can be achieved after strain-hardening through recrystallization for materials which do not exhibit phase transformations. The grain refinement during hot deformation of high stacking fault energy (SFE) materials, such as aluminium alloys, is usually explained by continuous dynamic recrystallization (CDRX) [1, 2] or geometric dynamic recrystallization (GDRX) [3, 4, 5, 6, 7, 8]. Different dynamic recrystallization phenomena during hot deformation of metallic materials have been recently reviewed by Huang and Logé [9]. The traditional CDRX mechanism, where low angle grain boundaries (LAGBs) formed during deformation progressively transform into high angle grain boundaries (HAGBs) when deformation continues, does not consider stable grain orientations inside which the misorientation of LAGBs saturates and never transform them into HAGBs even at larger strains [10, 11]. The formation of (micro)shear bands [9, 10], frequently observed during low deformation temperatures or high strain rates, is also not considered in this mechanism. Some authors even argued that CDRX does not exist, GDRX or dynamic recovery being enough to explain the observed grain refinement at large strains [12]. Later evidences, supported by the extensively studied on hot deformation of Al alloys [1,13,14], have proved that traditional CDRX does occur to a certain extent, especially when there is a change of strain path or when deformation is dominated by shear [9]. However, it was found that stable orientations persist even after severe plastic deformation, where the deformation route changes and strong shear deformation is usually involved [10]. It appears that there is currently no satisfactory theory accounting for all observed grain refinement mechanisms during hot deformation of high SFE materials.

In this study, samples of Al-1%Mg with coarse equiaxed initial grain size were deformed in different thermomechanical conditions by hot compression tests on a Gleeble 3800 machine, at strains far below the critical strain for GDRX [9, 13]. Microstructure evolutions were examined systematically by EBSD, and the connection to flow stress behavior was discussed.

2. Experimental

The as-received material was a direct chill cast Al-1% Mg, supplied by Novelis Switzerland. Due to the high solubility of Mg in Al, this material has limited second-phase particles, which makes the interpretation of the experimental results easier since it is well known that second-phase particle may interact with deformation [13] and recrystallization [15]. The as-received material has a very coarse initial grain size, more than 1500μm, as shown in Fig.1. The thermomechanical processing in this research was carried out by hot compression using a Gleeble 3800 machine. Cylindrical compression samples with dimensions 15mm×10mm (height × diameter) were machined from the as-received material. A J-type thermocouple was welded to the sample to monitor and control the temperature of the test specimens. The samples were lubricated with a thin layer of graphite foil. They were heated at 5°C/s to the target temperature and soaked for 3min at that temperature. Due to the excellent thermal conductivity of Al alloys, the temperature gradient within the sample is less than 2°C. The deformation was conducted under different temperatures (300°C and 400°C) and strain rates ($0.01s^{-1}$ and $0.1s^{-1}$). Deformation was interrupted at different strain levels, i.e., 0.2, 0.4, 0.6, 0.8 and 1.0, to follow the microstructure evolution. Deformed samples were quickly air quenched after deformation to avoid static recrystallization.

The deformed samples were cut parallel to the compression axis along the centerline. They were mechanically grinded and polished according to standard metallographic procedures, a final electro-polishing step (using electrolyte Struers A2 at room temperature at 30 V for 18 s) was applied to remove the deformed layer during mechanical polishing. Inverse pole figure (IPF) maps of the these samples, represented with respect to the compression direction (CD), were obtained by Electron backscatter diffraction (EBSD) in a FEI XLF 30 field emission gun scanning electron microscope (FEG-SEM) using the HKL software. For each condition, at least an area of size 500 μm × 370 μm (always in the center of the polished surface) was scanned using a fine step size of 0.4μm in order not to miss subgrain boundaries, even though only smaller maps are typically illustrated below to highlight some of the fine scale features. Grain boundaries with misorientation angles $\theta > 15°$ were considered as high angle grain boundaries (HAGBs), and those with orientation angles $1° < \theta < 15°$ were designated as low angle grain boundaries (LAGBs).