MATERIALS CHARACTERIZATION 75 (2013) 101–107

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Texture analysis of the effect of non-basal slip systems on the dynamic recrystallization of the Mg alloy AZ31

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A R T I C L E D A T A

Article history:
Received 17 August 2012
Received in revised form
3 October 2012
Accepted 7 October 2012

Keywords:
Magnesium alloys
Dynamic recrystallization
Non-basal slip systems

A B S T R A C T

The influence of non-basal slip systems on the dynamic recrystallization of a rolled and annealed Mg AZ31 sheet has been examined with the aim of investigating the relation between the deformation and recrystallization mechanisms in this alloy. With that purpose, the material was tested at 10^{-3} s^{-1} in tension along the rolling direction (RD), a condition under which prismatic <a> slip and basal slip are the main deformation mechanisms, and in compression along the normal direction (ND), where pyramidal <c+a> slip and basal slip predominate. The evolution of the microstructure and the texture at temperatures between 25 °C and 300 °C was examined. The optimum conditions for the onset of discontinuous dynamic recrystallization in this alloy appear to be those in which all three slip modes, i.e., basal, prismatic, and pyramidal <c+a> slip are active.

1. Introduction

Magnesium alloys have received great attention as high potential structural materials in the fields of aerospace, automotive and electronics owing to their low density, high specific strength, good dimensional stability, machinability and high damping capacity [1–3]. However, due to their hexagonal symmetry, the workability of these materials is limited. In order to address this issue, a large number of studies have been carried out to date on single crystals, polycrystals and by modeling in order to understand the deformation and recrystallization mechanisms at a wide range of temperatures [4–15]. Possible slip systems include three basal ((0001)<a>), three prismatic ($\left\{10\bar{1}0\right\}$<a>) and twelve pyramidal ($\left\{10\bar{1}1\right\}$<a> and $\left\{11\bar{2}2\right\}$<c+a>). Additionally, six $\{10\bar{1}2\}$ extension twinning systems and a total of twelve $\{10\bar{1}1\}$ and $\{10\bar{1}3\}$ contraction twinning [3] systems are also available. The critical resolved shear stress (CRSS) values for single crystals were the subject of early studies [11–13] and have been lately revisited by Chapuis et al. [7]. It is agreed that, at room temperature, $CRSS_{basal} < CRSS_{extension\ twinning} < CRSS_{prismatic} < CRSS_{pyramidal}$. The relative ratio of these CRSS values depends on the alloying additions, the grain size, the strain rate and the temperature. The exact CRSS values for polycrystalline materials are not known, as different studies have provided widely scattered data, but the trend is known to be similar [9,14]. The activation of each deformation mechanism is highly dependent on the texture as well as on the testing temperature and strain rate [15].

Understanding the recrystallization mechanisms during hot working of magnesium alloys is also a key to improve workability, to control the grain size and the texture and, thus, to alter the final properties. Several recrystallization mechanisms were observed to be operative in Mg alloys, namely continuous dynamic recrystallization (CDRX), discontinuous dynamic recrystallization (DDRX), twinning induced dynamic recrystallization (TDRX) and particle stimulated nucleation (PSN) [15]. DRX has been found to be strongly related to the operative slip and twinning systems [16–22]. Most studies agree that recrystallization occurs readily when multiple slip

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1044-5803/$ – see front matter
http://dx.doi.org/10.1016/j.matchar.2012.10.002

operates [16–22], i.e., when both basal and non-basal systems contribute to deformation. However, the role of specific non-basal slip systems in promoting DRX is still not well understood.

This work aims to contribute to this discussion by analyzing the separate contributions of prismatic <a> and pyramidal <c+a> slip to the enhancement of dynamic recrystallization in a Mg AZ31 sheet alloy. With that purpose, we have followed the evolution of the microstructure and of the texture of this material during compression along the normal direction (ND), a condition in which basal and pyramidal <c+a> slip are the main contributors to deformation [23] and also during tension along the rolling direction (RD), where the predominant active slip systems at low temperatures are basal and prismatic slip and where, additionally, the incidence of pyramidal <c+a> slip increases with temperature [24–27].

2. Material and Methods

The material used in this study was the commercial Mg alloy AZ31 (Mg–3%Al–1%Zn) purchased from Magnesium Elektron in the form of a rolled and annealed sheet of 3 mm in thickness. The initial microstructure consists of equiaxed grains, with an average grain size of 13 μm and a characteristic strong basal fiber texture (c-axes mostly parallel to ND) with a slight spread of the (0001) poles toward RD.

Mechanical tests were carried out along two different specimen directions in order to promote the activation of different non-basal slip systems upon yielding. In particular, tension tests were performed along RD, a condition under which prismatic and basal slip are the main contributors to deformation, and compression tests were carried out along ND, where the main active slip systems are pyramidal <c+a> and basal slip [23–27]. Special care was taken to choose orientations where tensile twinning was not favored in order to isolate the influence of the operative non-basal systems on dynamic recrystallization. Tensile specimens having a gage length of 15 mm, a width of 4 mm and a thickness of 3 mm and compression specimens with $3\times3\times3$ mm^3 were machined by an electric discharge process. Mechanical tests were carried out at 50, 100, 125, 150, 200, 250 and 300 °C at a strain rate of 1×10^{-3} s^{-1} in an SERVOSIS ME–405/10 electromechanical machine. The temperature of the sample during testing was measured using a K-type thermocouple. Some tests were interrupted at intermediate strains in order to track the microstructural evolution with deformation. The strain was estimated from the displacement of the crosshead, and the stress–strain data were treated in order to account for the stiffness of the testing machine. The 0.2% offset yield strength was measured from the treated stress–strain curve. Three tests were carried out for each condition.

Examination of the microstructure and the macrotexture of the tested samples were performed on the RD-TD plane using a combination of characterization techniques. Optical microscopy (OM) with polarized light was performed in an Olympus BX51 optical microscope. Sample preparation for OM consisted on gentle grinding with 600, 1200 and 2000 grit sand papers followed by polishing with 9 μm, 3 μm and 1 μm diamond pastes and with a 0.5 μm colloidal silica solution. The polished samples were finally etched with a solution of 10 ml acetic acid, 4.2 g picric acid, 10 ml water, and 70 ml ethanol. Measurement of the average grain size was carried out by the linear intercept method on the optical micrographs. X-ray texture measurements were carried out using Cu Kα radiation in a Panalytical Xpert Pro MRD diffractometer equipped with a PW3050/60 goniometer. The incomplete (0002), $\left(10\bar{1}0\right)$, $\left(10\bar{1}1\right)$, $(10\bar{1}2)$, $(10\bar{1}3)$ and $(11\bar{2}0)$ pole figures were measured up to a polar angle of 75° and, from them, the orientation distribution function (ODF) was calculated using the MTex software [28]. The sample preparation procedure for texture measurement was the same as that described above.

3. Results and Discussion

Fig. 1 illustrates the engineering stress–strain curves corresponding to the AZ31 rolled sheet deformed under tension along RD and under compression along ND at all the temperatures investigated. Some compression tests were stopped at the strain at which an increase of the stress associated to bulging was observed. Tension tests were all stopped at a strain of 0.3. In all cases the shape of the stress–strain curves is concave down, which is consistent with the absence (or with a very minor contribution) of twinning. Upon yielding, prismatic <a> slip is the predominant non-basal slip system in tension along RD and pyramidal <c+a> slip is considered the main non-basal slip system in compression along ND, as reported in the literature [23–27]. In tension, at room temperature, strain hardening takes place almost until failure. As temperature increases, a strain hardening stage is followed by strain softening. The strain at which the maximum stress is achieved decreases with increasing temperature. In compression, strain hardening takes place until failure at temperatures equal or lower than 100 °C. At higher temperatures, strain softening follows the strain hardening stage. At 125 °C, 150 °C and 200 °C the softening rates are larger than those observed at higher temperatures and in the tension tests.

Fig. 2 compares the evolution of the 0.2 offset yield strength (σ_y) values with increasing temperature corresponding to tension and compression tests. The relation between the yield strength and the critical resolved shear stress (CRSS) of the predominating slip systems in polycrystalline Mg alloys is not clear [29]. The yield stress (σ_y) is related to the CRSS of the various operating deformation mechanisms as $\sigma_y = m\tau_0 + mkd^{-1/2}$, where m is the Taylor factor, τ_0 is the CRSS for the operative slip systems and k is the microstructural shear stress intensity characterizing the average grain boundary resistance to plasticity spreading between the grains. Thus, the sensitivity of the CRSS of the operative deformation modes to temperature may be inferred roughly by analyzing the variation of σ_y with T. In the two cases examined in this study, and taking into account that the CRSS for basal slip is reportedly constant with temperature [9], it can be assumed that the variation of σ_y with T in the tension and compression tests is due mainly to the temperature dependence of the CRSS of the corresponding non-basal slip