Materials Science and Engineering A 519 (2009) 77–87

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

# Effect of reduction ratio on annealing texture and *r*-value directionality for a cold-rolled Al–5% Mg alloy

Shi-Hoon Choi[a,*], Jae-Kwon Choi[a], Hyoung-Wook Kim[b], Seok-Bong Kang[b]

[a] *Department of Materials Science and Metallurgical Engineering, Sunchon National University, 315 Maegok, Sunchon 540-742, Republic of Korea*
[b] *Korea Institute of Materials Science Research Station, Changwon 641-831, Republic of Korea*

ARTICLE INFO

*Article history:*
Received 21 January 2009
Received in revised form 12 May 2009
Accepted 28 May 2009

*Keywords:*
Annealing
Cold-rolling
VPSC
Volume fraction
*r*-Value

ABSTRACT

The evolution of the macrotexture and *r*-value directionality of cold-rolled Al–5% Mg alloys during annealing at various temperatures was investigated to seek an optimum annealing condition to improve the formability of TRBs. The change of volume fractions for the typical texture components of Al–5% Mg alloys was calculated using a misorientation approach in 3-D Euler space. A visco-plastic self-consistent (VPSC) polycrystal model was used to predict *r*-value directionality of the cold-rolled and annealed Al–5% Mg alloys. The electron backscatter diffraction (EBSD) technique was used to investigate a rapid change of the initial deformation texture in the specimen deformed by a reduction of 9% during annealing. The results showed that an optimum annealing temperature for achieving the low planar anisotropy was strongly dependent on the rolling reduction ratio.



## 1. Introduction

Transport manufacturers, such as the aircraft and automotive industries, require lightened materials with excellent mechanical properties. In particular, the use of light metals, such as aluminium and magnesium alloys, has increased in the manufacturing of automotive parts. However, since light metals have poor formability in comparison with steel, the optimization of microstructure and forming conditions is required [1,2]. Microstructure has been controlled through the optimization of the design, rolling and heat treatment conditions of alloys.

Optimization in both strength and weight can be achieved by using load-adapted blanks, e.g. tailor-welded blanks (TWBs) and tailor-rolled blanks (TRBs) [3–6]. A peculiar characteristic of these blanks is that thicker material is used in the parts sustaining higher loads, whereas thinner materials are used in the parts sustaining lower loads. Since the welding seam areas have mechanical properties different from the matrix, TWBs can exhibit lower ductility and formability in comparison with blanks without welding zones. Therefore, the application of TWBs is limited to a fewer number of expedient areas and non-critical deformation parts. On the other hand, TRBs, with longitudinal thickness transitions can be produced by a controlled online adjustment of the roll gap. Therefore, TRBs are used for expedient areas and critical deformation parts. To optimize the formability of TRBs, it is necessary to understand the effects of the reduction ratio of cold-rolling and annealing conditions on the microstructure and mechanical properties of annealed specimens. Macroscopic anisotropy of aluminium alloys has been widely studied due to its importance in forming process design [7–11]. The microstructural parameters that affect the macroscopic anisotropy of an aluminium alloy are the crystallographic texture, morphological texture such as grain shape, precipitate distribution and dislocation structure [11,12]. Among these parameters, crystallographic texture is the most dominant and determines the macroscopic anisotropy. Plastic strain ratio (*r*-value, or Lankford parameter) and its planar anisotropy have been used as a measure of macroscopic anisotropy [12]. The ratio of width strain/thickness strain, as measured using a simple uniaxial tension test, can be used to determine the *r*-value, which is closely related to the crystallographic texture developed in polycrystalline materials. Crystallographic texture can be developed in cold-rolled and annealed specimens. Deformation texture in cold-rolled aluminium alloys is composed of $\alpha$- and $\beta$-fibers [13–16]. Evolution of the deformation texture in cold-rolled aluminium alloys can be influenced by the initial texture, strain path and alloy composition. It is known that the annealing texture of aluminium alloys is influenced by recovery before annealing [17], by pre-treatment [18] and by annealing temperature and time [17–19]. These studies on annealing texture evolution in 5000 series aluminium alloys containing Mg from 4.5 to 5.5 wt% have been conducted at a fixed reduction ratio of cold-rolling [17–20]. These studies did not capture the effect of the reduction ratio on the

* Corresponding author. Tel.: +82 61 750 3556; fax: +82 61 750 3550.
*E-mail address:* shihoon@sunchon.ac.kr (S.-H. Choi).

0921-5093/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2009.05.063

annealing texture and on macroscopic anisotropy in aluminium alloys.

In the present study, the cold-rolling process was performed using a commercial Al–5% Mg alloy at different reduction ratios to investigate the evolution of deformation texture in TRBs. The evolution of the macrotexture and *r*-value directionality of cold-rolled Al–5% Mg alloys during annealing at various temperatures was also investigated to seek an optimum annealing condition to improve the formability of TRBs. The evolution of the volume fraction for the typical texture components of Al–5% Mg alloy was calculated using the misorientation approach in 3-D Euler space. Moreover, the *r*-value directionality was simulated using a visco-plastic self-consistent (VPSC) polycrystal model. The ODF, as determined by Gaussian standard function, was used to research the effect of texture components typical in Al–5% Mg alloy on the *r*-value directionality. The effect of the reduction ratio and the annealing temperature on the *r*-value directionality of an annealed Al–5% Mg alloy also was investigated.

## 2. Experimental

The material used in the present investigation was a commercial Al–5% Mg alloy of 1.6 mm thickness. To determine the effect of reduction ratio on the annealing texture, the as-received specimens were cold-rolled to 9, 17, 39 and 65% reductions in thickness. The roll diameter and roll speed were 210 mm and 5 rpm, respectively. The cold-rolled specimens were annealed at 350, 400 and 450 °C for 1 h in a box furnace followed by air cooling. The microstructure of the cold-rolled and annealed specimens was observed using a polarized light in an optical microscope. All microstructures were observed in longitudinal sections as defined by their RD (rolling direction) and ND (normal direction). The macrotexture measurements of the initial specimens were conducted on RD–TD (transverse direction) sections at the center, the intermediate and the surface to analyze texture gradients through the thickness direction. Macrotexture measurements of the cold-rolled and annealed specimens were conducted on RD–TD sections at the centers. The surfaces of the specimens were carefully polished to minimize surface stress. The (1 1 1), (2 0 0) and (2 2 0) incomplete pole figures were measured to a maximum tilt angle of 70° using the Schulz back-reflection method with Cu Kα radiation. After background and defocusing corrections, the orientation distribution functions (ODFs) were calculated from the incomplete pole figures using the WIMV method [21]. The electron backscatter diffraction (EBSD) technique was used to analyze the microtexture of as-received and annealed specimens showing a competitive grain growth. The initial specimen was cut from the RD–ND section. The specimens showing a competitive grain growth were cut from the RD–TD section at center. The EBSD specimens were prepared using colloidal silica as the polishing medium for the intermediate stage. The final specimens were prepared by electro-polishing in A2 electrolyte for the final stage. The EBSD data were analyzed using TSL software to evaluate 3-D ODF.

## 3. Theoretical analysis

### 3.1. Calculation of volume fraction for texture components

To evaluate the evolution of the macrotexture during the cold-rolling and annealing processes, the volume fraction of the texture components typical in Al–5% Mg alloy was calculated using a misorientation approach in 3-D Euler space [22]. The orientation of a crystal coordinate, $K_B$, with respect to the sample coordinate, $K_A$, can be expressed by three Euler angles, $g = \{\varphi_1, \Phi, \varphi_2\}$ in the Bunge notation [23]. The 3-D Euler space (or *G* space) contains every orientation, g, that describes the transformation of $K_A$ into $K_B$, as follows:

$$K_B = g \cdot K_A \quad g : [K_A \to K_B] \text{ or } g^{-1} = g^T : [K_B \to K_A] \tag{1}$$

Since the Euler space is finite with either the space element, or the volume element, the volume can be expressed mathematically, as follows:

$$\int_G \mathrm{d}g = 8\pi^2 \qquad \mathrm{d}g = \mathrm{d}\varphi_1 \sin\Phi \, \mathrm{d}\Phi \, \mathrm{d}\varphi_2 \quad G : 0 \le \varphi_1, \; \varphi_2 \le 2\pi;\; 0 \le \Phi \le \pi \tag{2}$$

Assuming orthorhombic sample symmetry, the Euler space can be reduced, as follows:

$$\int_G \mathrm{d}g = \frac{\pi^2}{4} \qquad \mathrm{d}g = \mathrm{d}\varphi_1 \sin\Phi \, \mathrm{d}\Phi \, \mathrm{d}\varphi_2 \quad G : 0 \le \varphi_1, \varphi_2, \Phi \le \frac{\pi}{2} \tag{3}$$

When the orientations of discrete points are known of a body with volume *V*, the ODF, *f*(*g*), is given by the following equation:

$$f(g) = \frac{\mathrm{d}V(g)}{\mathrm{d}g} \tag{4}$$

To calculate the volume fraction of the typical texture components in an Al–5% Mg alloy, the 3-D Euler space can be subdivided into a 5° × 5° × 5° grids. The summation of the discrete ODF over all the cells in the 3-D Euler space should be unity, as follows:

$$1 = \frac{4}{\pi^2}\sum_{\varphi_1}\sum_{\Phi}\sum_{\varphi_2} f(\varphi_1, \Phi, \varphi_2)\Delta\varphi_1 \;\; \Delta\varphi_2 \sin\Phi \, \Delta\Phi \tag{5}$$

The volume fraction of texture components can be calculated by summation of these products over the set of cells associated with the texture component. The misorientation between orientations in the 3-D Euler space was evaluated, as follows:

$$\theta = \min\left[a \cos\left\{\frac{\mathrm{trace}(S_\nu \cdot (g_2^{-1} \cdot g_1)) - 1}{2}\right\}\right] \tag{6}$$

where $S_\nu$ is the crystal symmetry operator and $\nu$ takes values ranging from 1 to 24 for cubic crystal symmetry. A specific cut-off angle was chosen and all cells in the 3-D Euler space, with a misorientation angle that fell within the cut-off, were included in the summation to obtain the volume fraction. In the present study, 15° was used as the cut-off angle. The algorithm of Section 3.1 has been implemented in Fortran 77 in double precision.

### 3.2. VPSC polycrystalline model for simulation of r-value directionality

The VPSC polycrystal model was used in order to simulate the *r*-value directionality in an Al–5% Mg alloy under uniaxial loading. The shear rate of slip system *s*, $\dot{\gamma}^s$, is related to the resolved shear stress, $\tau^s$, by a power law relationship, which is called the visco-plastic law:

$$\tau^s = \tau_o sgn(\dot{\gamma}^s)\left|\frac{\dot{\gamma}^s}{\dot{\gamma}_o}\right|^m = \tau_o \frac{\dot{\gamma}^s}{\dot{\gamma}_o}\left|\frac{\dot{\gamma}^s}{\dot{\gamma}_o}\right|^{m-1} \tag{7}$$

where *m* is the rate sensitivity, and $\dot{\gamma}_o^s$ and $\tau_o^s$ are the reference shear rate and the reference critical resolved shear stress, respectively. The microscopic hardening law of single crystals can be taken into account by changing the critical resolved shear stress, $\tau_o^s$. The sign term in Eq. (7) means that the shear rate has the same sign as the resolved shear stress. The resolved shear stress is related to the Cauchy stress tensor, $\sigma_{ij}$, of the crystal through the following relationship:

$$\tau^s = \tilde{\sigma} \cdot \vec{n}^s \otimes \vec{b}^s = m_{ij}^s \sigma_{ij} \tag{8}$$