Materials Science and Engineering A 508 (2009) 121–128

Contents lists available at ScienceDirect

Materials Science and Engineering A

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

Interpretation of the strain state during cross-roll rolling of aluminum by means of texture analysis

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ARTICLE INFO

Article history:
Received 17 November 2008
Received in revised form 12 December 2008
Accepted 12 December 2008

Keywords:
Cross-roll rolling
Shear deformation
Strain state
Finite element method

ABSTRACT

Cross-roll rolling of aluminum alloy sheets was carried out in which the roll axes are tilted by ±7.5° away from the transverse direction of the rolled sample. The evolution of strain states during cross-roll rolling was studied by three-dimensional finite element method (FEM) simulations. The strain states calculated by FEM were verified by texture analysis. Cross-roll rolling was found to impose a large uniform shear strain $\dot{\varepsilon}_{23}$ in the whole sheet thickness; nevertheless, cross-roll rolling gives rise to the formation of plane strain texture plus an asymmetrical rotated cube orientation {0 1 2} ⟨1 0 0⟩. After recrystallization, the large shear strain $\dot{\varepsilon}_{23}$ led to a refinement of the microstructure, which may be beneficial to the formability of cross-roll rolled aluminum alloy sheet.

1. Introduction

Recently, Chino et al. have proposed a new rolling method in which the roll axes are tilted about the normal direction (ND) in the rolling direction (RD)–transverse direction (TD) plane, as shown in Fig. 1 [1–3]. In this process, a significant proportion of shear deformation along the TD is expected because a thrust force in axial direction of the rolls is imposed on the rolled sheet. Since the rolls are crossed in the RD–TD plane, this rolling process is referred to as “cross-roll” rolling (which is not to be confused with conventional cross-rolling in which the RD is rotated after each rolling pass [4–9]).

Chino et al. reported that cross-roll rolling is effective for the imposition of a severe shear straining on rolled materials, leading to a refinement of the microstructure and an improvement in formability of magnesium alloy sheets [1–3]. Obviously, the deformation mode during cross-roll rolling differs from that during normal rolling; nevertheless, detailed studies on the evolution of strain states during cross-roll rolling are lacking to date.

In the present study, the evolution of strain states during cross-roll rolling was calculated along certain through-thickness streamlines by three-dimensional finite element method (FEM) modeling. Parallel to the FEM simulations, an aluminum alloy having a nearly random initial texture was cold rolled in a cross-roll rolling mill and the resulting textures were analyzed by quantitative texture analysis. In order to confirm the FEM-derived strain states during cross-roll rolling, strain histories at various thickness layers were fed into a visco-plastic self-consistent (VPSC) code for texture simulation [10–14]; finally the simulated textures were compared to the experimental textures.

2. Experimental procedure

The experiments were performed with the commercial aluminum alloy AA 5052 (Al–2.5%Mg–0.3%Cr–0.3%Fe–0.2%Si). The as-received hot band with a thickness of 16 mm was first cold rolled to 6 mm in a rolling mill having roll diameters of 300 mm in which rolling was operated with different roll speeds of upper and lower rolls [15–17]. This asymmetrically rolled sheet was then soft annealed to produce the initial sample for the cross-roll rolling experiments. The initial sample displayed a fairly random texture and equiaxed recrystallized grains with an average diameter of 25 μm.

Cross-roll rolling was carried out in a laboratory rolling mill in which the roll axes are tilted by ±7.5° away from the TD in the RD–TD plane (Fig. 1). The initial sample with a thickness of 6.0 mm and a width of 60 mm was cold rolled by four passes of cross-roll rolling with maintaining the original RD to a thickness of 1.0 mm, corresponding to a thickness reduction of 83%. Note that in the present study cross-roll rolling was carried out without lubrication in order to increase shear deformation. More details on the method of cross-roll rolling can be found in Refs. [1–3].

The macro-textures of the various through-thickness layers were determined by standard X-ray texture analysis. The thickness layer within a sheet is indicated by the parameter s, where $s = 1.0$ and 0.0 denote the surface and center layer such that $s = 0.5$ identifies the quarter layer between surface and center. From three pole

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0921-5093/$ – see front matter
doi:10.1016/j.msea.2008.12.028

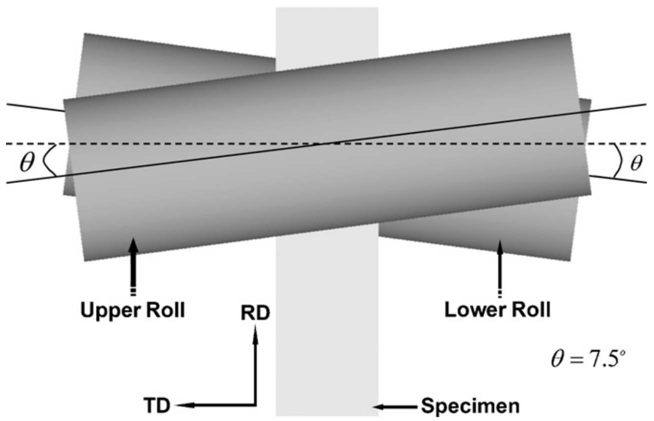

Fig. 1. Schematic diagram of the cross-roll rolling mill (top view).

figures the three-dimensional orientation distribution functions (ODF) were calculated by the series expansion method according to Bunge (l_{max} = 22) [18]. For details on measurement and representation of texture data, see Ref. [19].

In order to investigate the impact of cross-roll rolling on the evolution of microstructure after recrystallization, the cold-rolled sheets were finally soft annealed at 400 °C for 30 min. The resulting microstructures were analyzed by electron back-scatter diffraction (EBSD) in a SEM [19].

3. Results

3.1. Calculation of strain states during cross-roll rolling

To a very rough approximation for macroscopic sheet, standard rolling deformation is plane strain compression for which $\dot{\varepsilon}_{11} = -\dot{\varepsilon}_{33}$ and all other strains $\dot{\varepsilon}_{22} = \dot{\varepsilon}_{12} = \dot{\varepsilon}_{13} = \dot{\varepsilon}_{23} = 0$ (the indices 1, 2 and 3 respectively indicate RD, TD and ND of a sheet). In the practical rolling process, appreciable amounts of shear deformation $\dot{\varepsilon}_{13}$ may take place because of the geometrical shape change in a roll gap and the friction between the sample surface and rolls. However, the strain state accompanied with standard rolling is still approximated by a two-dimensional problem with $\dot{\varepsilon}_{11} = -\dot{\varepsilon}_{33}$ and $\dot{\varepsilon}_{13} \neq 0$, where the other strain components involving TD – i.e. $\dot{\varepsilon}_{22}$, $\dot{\varepsilon}_{12}$ and $\dot{\varepsilon}_{23}$ – are zero. Because of the specific cross-roll rolling geometry (Fig. 1), operation of shear components along TD – i.e. $\dot{\varepsilon}_{12}$ and $\dot{\varepsilon}_{23}$ – is expected during cross-roll rolling. Therefore, the strain state accompanied with cross-roll rolling is a three-dimensional problem involving $\dot{\varepsilon}_{13}$, $\dot{\varepsilon}_{12}$ and $\dot{\varepsilon}_{23}$. Operation of each $\dot{\varepsilon}_{13}$, $\dot{\varepsilon}_{12}$ and $\dot{\varepsilon}_{23}$ in a roll gap results in a net change in grain shape as shown in Fig. 2 [20].

In the present study the evolution of strain states during cross-roll rolling was calculated by three-dimensional FEM using the commercial FEM package DEFORM^{TM}-3D. For details on the FEM simulation scheme regarding rolling deformation, see Refs [15,16,21–23]. The high friction during rolling without lubrication was accounted for by using a quite large friction coefficient of μ = 0.3 [24]. The resulting variations of the shear strain components $\dot{\varepsilon}_{13}$, $\dot{\varepsilon}_{12}$ and $\dot{\varepsilon}_{23}$ along three streamlines with s = 1.0, 0.5 and 0.0 are displayed in Fig. 3. Note that the FEM simulations were carried out in the center of the width of the samples.

As already mentioned above, rolling of thin strip is often simplified by a plane strain state. However, in the thickness layers away from the center plane appreciable amounts of shear deformation $\dot{\varepsilon}_{13}$ may take place. In particular, rolling with large rolling draughts and/or high friction is known to give rise to large variations of $\dot{\varepsilon}_{13}$ along a given streamline in the roll gap. This results in pronounced through-thickness texture gradients as comprehensively reported elsewhere [22–28].

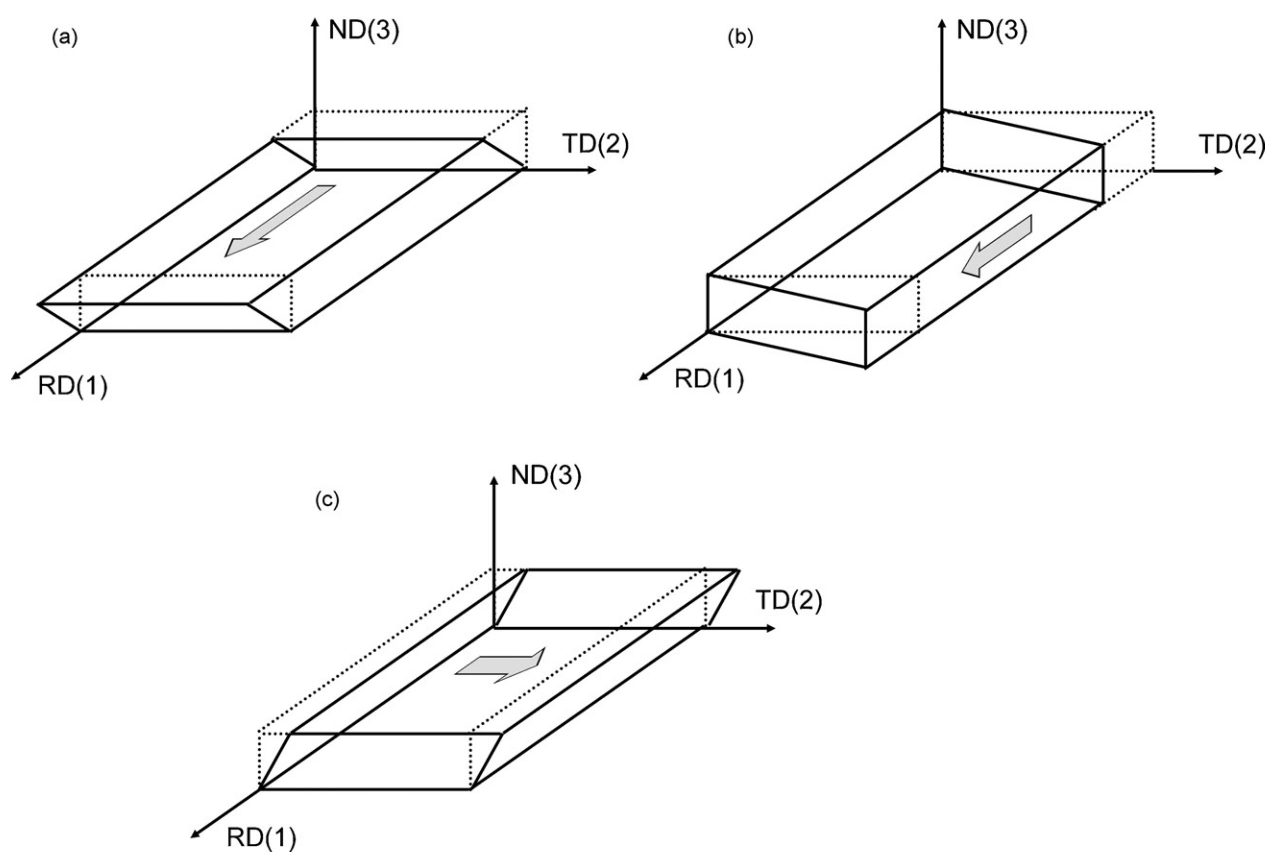

Fig. 2. Schematic diagram showing shear strains developed during rolling. (a) $\dot{\varepsilon}_{13}$, (b) $\dot{\varepsilon}_{12}$ and (c) $\dot{\varepsilon}_{23}$.