General paper

The Evolution of Shear Deformation Texture and Grain Refinement in Asymmetrically Rolled Aluminum Sheets

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Abstract: Asymmetric rolling, in which the ratio of upper to lower roll diameter is different, has been used to introduce an intense plastic shear strain for the purpose of obtaining higher plastic strain ratios due to uniform development of shear deformation textures through the thickness and of grain refinement in aluminum sheets. A commercial purity aluminum sheet was asymmetrically cold rolled under various schedules. The textures, microstructures and strengths of the rolled sheets were investigated. When subjected to several passes of asymmetric rolling by over 90%, the textures approaching to the ideal shear deformation texture consisting of $\{001\}\langle 110 \rangle$, $\{111\}\langle 110 \rangle$ and $\{111\}\langle 112 \rangle$ developed throughout the thickness. Transmission electron microscopy and electron back-scatter diffraction analyses showed that the sheets have fine-grained structures with large misorientations. Unidirectional rolling in which the rolling direction does not change between passes gave rise to more uniformly refined structures than alternating direction rolling in which the rolling direction is rotated through 180° about the rolling direction between passes.

Key words: Asymmetric rolling, Aluminum, Shear deformation texture, Grain refinement

1. INTRODUCTION

Asymmetric rolling (Fig. 1), in which the circumferential velocities of work rolls are different, is a novel technique to introduce an intense plastic shear strain of a sheet [1-8]. Unlike conventional or symmetric rolling, which can introduce shear deformation only in the surface region of sheet, asymmetric rolling gives rise to the shear strain throughout the thickness. Recent studies have reported that the shear deformation can develop shear deformation textures in aluminum alloy sheets for the purpose of the improvement of their plastic strain ratios and in turn deep drawabilities [1-13]. The ideal components of shear deformation textures of fcc metals are $\{001\}\langle 110 \rangle$, $\{111\}\langle 110 \rangle$ and $\{111\}\langle 112 \rangle$, among which ND// $\{111\}$ texture is the most favorable components for the drawability of sheets [2,3,14]. Table 1 shows plastic strain ratios predicted for some ideal orientations [14]. Recent studies have reported that the uniform development of shear deformation textures by asymmetric rolling can improve plastic strain ratios of aluminum alloy sheets [2,5-8].

As well as the texture development, the severe shear deformation has been focused on as an effective method of producing fine-grained materials. Several processes have been proposed for the grain refinement, such as torsion straining [15,16], equal channel angular pressing (ECAP) [17-23] and recently asymmetric rolling [24]. Though ECAP has been considered to be a simple and

prospective method, asymmetric rolling is more practical and feasible for fabrication of large-scale sheets. For the effective refinement by asymmetric rolling, the control of rolling conditions is important, because the rolling process gives rise to the non-uniform strain distribution through the thickness. There is lack of understanding the evolution of the texture and microstructure in asymmetrically rolled aluminum sheet in terms of rolling conditions.

Fig. 1. Schematic diagram of asymmetric rolling process ($R_1:R_2=V_1:V_2$).

Table 1. Plastic strain ratios predicted for some ideal orientations [14].

Orientation	$\bar{R}$	ΔR
{111}<110>	1.91	0.04
{001}<100>	0.53	0.30
{110}<112>	1.35	0.46
{112}<111>	1.29	0.34
{123}<634>	1.27	0.35

In this study, AA1050 aluminum alloy sheets were asymmetrically rolled and their textures and a possibility of grain refinement in them were examined. The evolution of microstructure including grain boundary character in them was investigated by transmission electron microscopy (TEM) and electron backscatter diffraction (EBSD) analyses. Their strengths were also measured. The evolution of texture and microstructure along the thickness was investigated in terms of the rolling direction.

2. EXPERIMENTAL

The material used in this study was a 6.5mm thick AA1050 aluminum alloy (99.5%Al-Fe-Si) sheet, which was fully annealed at 400°C for 1h prior to rolling. The annealed sheet had an average grain size of about 25μm in the surface regions and about 45μm in the center region and the texture characterized by a weak shear deformation component in the surface layer and a strong cube component in the center layer. Asymmetric rolling was applied to the annealed sheet without lubrication at room temperature with a mill whose upper and lower roll diameters were 248mm and 128mm, respectively, at a rotation rate of 7 rpm. Two different rolling schedules were applied. The one is uni-directional rolling (UNI), in which the rolling direction and the specimen position are kept the same in all rolling passes. The other is alternating direction rolling (ALT), in which the rolling direction is unchanged, but the sheet is rotated about the rolling direction every rolling pass. The total reduction was about 91% through 12 passes in the both UNI and ALT rolling processes. The rolled sheets were annealed at 195°C for 1h.

The texture was measured with an X-ray diffraction goniometer in the back reflection mode with Fe filtered Co-K α radiation. The microstructure was observed under TEM. To investigate the grain refinement, the selected area diffraction pattern (SADP) was obtained. For the TEM foil preparation, the specimen was mechanically polished and then electro-polished in a nitric acid solution. The grain boundary structure was investigated by EBSD. The EBSD specimens were electro-polished in a solution consisting of perchloric acid and ethanol. JEOL JSM-

6300 SEM equipped with a Link ISIS OPAL system was employed.

The tensile test of the specimens was carried out at a crosshead speed of 1mm/min.

The deformation was analyzed by the elasto-plastic finite element method (FEM). In the analysis, the friction coefficient between rolls and material was assumed to be 0.4, because sticking friction occurred between rolls and material and the flow curve of aluminum was approximated by $\sigma=179\epsilon^{0.22}$ [25]. The undeformed aluminum was assumed to consist of 978 randomly oriented crystallites in each element. The strain increment history of each element was obtained and used to calculate crystallographic orientations based on the full constraints Taylor theory [26] together with the Renouard-Wintenberger theory [27]. The orientations were expressed as the Gaussian peaks with a scattering angle of 10° and superimposed to obtain distributions in pole figures [28].

3. RESULTS AND DISCUSSION

Figure 2 shows the calculated deformed meshes of aluminum sheets asymmetrically rolled by 50% at roll ratios of 1.25, 1.5, and 2.0. The deformed meshes show that the shear deformation can penetrate into the center with increasing the roll radius ratio.

Figure 3 shows the textures calculated by imposing the strains in Fig. 2 to random oriented specimens. It can be seen that an optimum roll radius ratio for the shear deformation textures being developed through the thickness exists and they deviated from the ideal shear deformation textures, {001}<110>, {111}<110> and {111}<112>.

Fig. 2. Deformed FEM meshes of aluminum sheets asymmetrically rolled by 50% at roll ratio of (a) 1.25, (b) 1.5 and (c) 2.

Fig. 3. Calculated $\{111\}$ pole figures of aluminum sheets asymmetrically rolled by 50% at roll radius ratios of (a) 1.25, (b) 1.5, and (c) 2.

Figure 4 shows $\{111\}$ X-ray pole figures of the 91% asymmetrically rolled sheets measured at upper surface, center and lower surface layers. The upper and lower surfaces of the specimen ALT indicate those of the final specimen, or those of sheet rolled through even number rolling passes. The textures of the rolled sheets are close to the ideal shear deformation textures, but their intensities are weak and tend to increase with moving from the upper surface to the lower surface. Figure 5 shows X-ray pole figures of the sheets in Fig. 4 after annealing at 195°C for 1h. The low temperature annealing did not change the macroscopic textures.

Figure 6 shows the bright field (BF) TEM microstructures of the upper surface, center, and lower surface layers of the 91% rolled specimens. The TEM specimens were thinned parallel to the rolling plane. SADPs were taken from the center of the BF images using an aperture of 3 μ m in diameter. The microstructures show that the specimens consist of fragmented or refined structures and the numerous spots in the SADPs indicate the presence of high angle grain boundaries. More sharply defined boundaries in the lower surface regions could be resulted from the dynamic recovery during rolling. Figure 7 shows the TEM BF images of the specimens in Fig. 6 after annealing at 195°C for 1h. The comparison of Fig. 6 with Fig. 7 indicates that grain coarsening took place during annealing.

Fig. 4. $\{111\}$ X-ray pole figures of AA1050 sheets asymmetrically rolled by 91% in unidirection (UNI) and alternating directions (ALT).

Fig. 5. $\{111\}$ X-ray pole figures of AA1050 sheets asymmetrically rolled by 91% in unidirection (UNI) and alternating directions (ALT) after annealing at 195°C for 1h.

In order to investigate characteristics of grain boundaries, EBSD mappings of the annealed specimens were carried out and the results are shown in Fig. 8. Uniformly distributed grain structures with high angle grain boundaries were developed in the UNI specimens. On the other hand, the ALT sheets exhibited less refined and non-uniform microstructures. It should be mentioned that the same directional shear strains were imposed to the UNI specimen, whereas the positive and negative shear strains were imposed to the ALT specimen. We do not understand how the differences in shear strain direction could cause such microstructures in the UNI and ALT specimens. Further studies are needed. Whatever reason it may be, it is apparent from the experimental results, UNI rolling give rise to grain refine-

ment more effectively than ALT rolling.

At this point, several reports of ECAP are worth mentioning, which demonstrated the effect of rotation of material each cycle on the grain structure. Iwahashi et al claimed that the subgrains evolve more rapidly into arrays of high angle boundaries by rotating a sample between each pass [20,21]. Contrary to this, a more recent investigation using EBSD analysis have reported that the most effective method of forming a fine-grained structure is to maintain a constant strain path [22]. The later result is consistent with the present result.

As stated above, the shear strain is an important factor for producing fine-grained structures and asymmetric rolling makes the shear strain penetrate into the center

region of the sheets. However, for the nature of the rolling geometry, the inhomogeneous strain distribution through the thickness is inevitable. In order to obtain a more uniform structure, higher shear strains through the thickness should be applied. The higher shear strains can be obtained by the higher reduction per pass [1]. The higher roll radius ratio does not necessarily give rise to the higher shear strains, because the higher ratio can lower the roll pressure [1,29]. The other rolling conditions will be friction between rolls and materials, rolling temperature, etc. There should be further studies to optimize asymmetric rolling parameters for successful grain refinement.

Fig. 6. TEM BF micrographs and SADPs of AA1050 sheets asymmetrically rolled by 91% in uni-direction (UNI) and alternating direction (ALT).

Fig. 7. TEM BF micrographs and SADPs of AA1050 sheets asymmetrically rolled by 91% in uni-direction (UNI) and alternating direction (ALT) after annealing at 195°C for 1h.

Fig. 8. EBSD analyses of AA1050 sheets asymmetrically rolled by 91% in unidirection (UNI) and alternating directions (ALT) after annealing at 195°C for 1h.

For comparison, the same initial AA1050 sheets were symmetrically rolled under lubrication by multiple-pass to have 91% reduction and annealed at 195°C for 1h. EBSD mapping of the specimens was carried out. The EBSD result is shown in Fig. 9. The figure shows coarse grains and low angle boundaries. This result also shows that shear strains are important for grain refinement.

The tensile strengths of the rolled specimens of UNI

and ALT together with symmetrically rolled AA1050 sheets with lubrication by multiple-pass are given in Table 2. The strengths of the specimen UNI and ALT are almost the same, but much higher than that of the symmetrically rolled sheet. The increase in strength is mainly due to the increase in the applied shear strains, which in turn gave rise to grain refinement and an increase in dislocation density.

Fig. 9. EBSD analyses of AA1050 sheets symmetrically rolled by 91% and annealed at 195°C for 1h.

Table 2. Tensile strengths of AA1050 sheets asymmetrically rolled by 91% in unidirection (UNI) and alternating directions (ALT) and symmetrically rolled.

	UTS, MPa
UNI	212
ALT	216
Symmetrically rolled	172

4. CONCLUSION

The textures of asymmetrically rolled AA1050 aluminum alloy sheets were approaching to the ideal shear deformation textures, $\{001\}<110>$ and $ND//\{111\}$, through the thickness. Fine-grained structures with high angle boundaries and hence high strengths were obtained by asymmetric rolling. However, the evolution of textures and grain structures in the rolled sheets were not uniform through the thickness. For a given asymmetric rolling reduction, unidirectional rolling gave rise to more uniformly refined structures than alternating direction rolling.

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