Cube Texture Development in an Al–Mg–Mn Alloy Sheet Worked by Continuous Cyclic Bending

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Changes in texture after the continuous cyclic bending (CCB) and the subsequent annealing in sheets of an Al–4.7 mass%Mg–0.7 mass%Mn alloy have been investigated. The CCB was recently proposed as a straining technique that generates a high strain on the surface and a much lower strain in the central layer of the sheet. The Cube texture in the surface layer is sharpened remarkably during the CCB process and the annealing that follows. The 50 CCB passes lead to a sharper texture in all layers of the sheet. After annealing, marked development of the Cube component is observed in the surface layer. On the other hand, for the 20 pass-CCBent sample, the Cube texture appears only after annealing in a salt bath, while this texture is not observed after annealing both in Ar and in air. The mechanism of texture formation and the effect of processing on the sharpening of Cube texture is discussed based on results obtained from the electron backscatter diffraction pattern (EBSP) analysis and from the *in-situ* measurement of X-ray peak intensity during heating.

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1. Introduction

Significant efforts have been made recently to develop high performance materials that are more environmentally friendly.¹⁾ Improvement of recyclability in materials requires simplifying and unifying chemical composition and limiting the use of rare or poisonous elements. Therefore, it may become more important to control the manufacturing process than the chemical composition. In other words, the microstructural control by thermomechanical treatment should play an important role in the development of innovative materials. There are two main strategies for improvement of properties by microstructural control through thermomechanical treatment. One of them is the grain refinement, and another is the control of grain orientation distribution. A typical example of the former is the equal channel angular pressing (ECAP) technique.²⁾ This technique uses ultra high straining to improve mechanical, physical and chemical properties through the grain refinement process, which is regarded as a typical production process that does not affect recyclability. Alternatively, the latter process is focused on control of both texture and microstructure. Because many physical, chemical and mechanical properties of crystals depend on crystallographic orientation, directionality or anisotropy of these properties in polycrystalline materials can be another factor that is expected to lead to the improvement of properties.

Takayama *et al.*³⁾ have proposed continuous cyclic bending (CCB) as a straining technique that can produce the high strain in the surface layer and the low strain in the central part of the metal sheet. These authors reported that the CCB process and subsequent annealing make it possible to produce the gradient microstructure with the coarse-grained surface

layer and the fine-grained layer in the middle of the sheet of Al–4.7 mass%Mg–0.7 mass%Mn alloy (A5083). This cyclic deformation straining technique leads to a definite difference in strain between the surface and central layers. Moreover, the formation of microstructure in the coarse-grained layers is very likely related to changes in texture. However, no investigation has been carried out on the textural aspect of microstructure.

The present study reports changes in texture after the CCB process and the subsequent annealing in sheets of the Al–Mg–Mn alloy. It reveals that the Cube texture in the surface layer is sharpened remarkably during the CCB process and the subsequent annealing. Further, mechanism and effect of processing on the Cube texture sharpening is discussed.

2. Continuous Cyclic Bending

The Continuous cyclic bending (CCB) method has been proposed as a useful straining technique for sheet materials.³⁾ Figure 1 illustrates the principle of CCB. As shown in this figure, a sheet is cyclic-bent continuously by passing between plural rolls. The rolls are arranged symmetrically with respect to the central point; this arrangement is similar to the roller leveler or the straightening facility for rolled sheets. The sheet is in practice fastened at the top, and the CCB device consisting of the four rolls moves down at a constant speed to apply the strain. The process enables, in principle, the infinite straining on the surface. True strain on the surface of the sheet given by bending is derived from a simple principle.⁴⁾ Based on this principle, the true strain per one pass of the CCB is expressed by the following equation:

$$\varepsilon = 2 \left\{ \ln \left(1 + \frac{1}{2R_1/t + 1} \right) + \ln \left(1 + \frac{1}{2R_2/t + 1} \right) \right\}, \quad (1)$$

where R_1 and R_2 are radii of inside and outside bending curvatures and t is the thickness of the sheet. True strain on the

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Fig. 1 Schematic illustration of Continuous Cyclic Bending (CCB).

Table 1 Chemical composition of AA5083 aluminum alloy used (mass%).

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.03	0.04	Tr.	0.65	4.70	0.10	Tr.	0.01	Bal.

surface given by a single pass of the CCB is calculated as 0.1056, assuming that the strains for both sides of bending in both directions can be added. When the number of passes of CCB, N_{CCB} is 50, the total strain is equal to be 5.28. This value corresponds to 99.5% of compressive nominal strain, and it represents a heavy deformation.

3. Experimental Procedure

The Al–4.7 mass%Mg–0.7 mass%Mn (A5083) alloy used in this study was produced by the Sky Aluminum Company, Japan. The material was received in the form of rolled sheets of 1.5 mm thick. The chemical composition is listed in Table 1. The as-received sheets had been manufactured by the process of casting, homogenizing (at 803 K), hot rolling, cold

rolling with a reduction of 75% and a final continuous annealing at 673 K. Workpiece was machined with a 500 mm length, a 20 mm width and a 1.5 mm thickness, and then was cyclic-bent continuously using a specially-designed device up to the maximum number of passes, $N_{CCB} = 50$. The CCB passes were carried out on both sides of the sheet alternately to keep the symmetry of straining. The longitudinal direction is parallel to the rolling direction. The sample coordinate system is defined by the rolling, transverse and normal directions (RD, TD and ND) according to common practice for rolled sheets. From the CCBent workpiece the specimens with of dimension of 25 mm × 15 mm × 1.5 mm were prepared for texture analysis. Some of these specimens were annealed at 673 K for 3.6 ks or 60 s after CCB process.

In the previous study,³⁾ changes in microstructure accompanying the CCB process and subsequent annealing were described. The microstructure of the CCB sample as observed using optical microscopy is not different from that of the as-received sample, however differences in the structure of the two samples were observed by transmission electron microscopy. For the annealed samples coarse-grained structures were observed in the surface layers. The thickness of the coarse-grained layer increased as annealing time or temperature increases. According to these results, the samples in the present study are selected as listed in Table 2. The samples were also annealed in Ar and in air to investigate the effect of annealing conditions.

Textures were examined on the surface and sub-surface layers at 1/4 and 1/2 of the specimen thickness using Siemens D-500 texture goniometer. Pole figures were measured using the reflection technique, up to 80° in 5° polar and radial intervals. The ODFs $f(g)$ were calculated from three incomplete pole figures namely {111}, {200} and {220} using the series expansion method⁵⁾ ($l_{max} = 22$). The planes examined represent the surface, middle and center layers, respectively. The depth is parameterized by the variable, s , the thickness parameter, which can be calculated by an equation, $s = (t_a - t_0/2)/(t_0/2)$, where t_a is the thickness of the sample with the surface removed, and t_0 is the original thickness of the sample. X-ray diffraction patterns at both temperatures were obtained using Rigaku rotating anode diffractometer for *in-situ* measurement of intensity of {200} peak during heating. The grain orientation analysis was performed

Table 2 Samples used and preparing procedures

Sample	N_{CCB}	Annealing condition after CCB	Note
0P	0	—	As-received, grain size: 6.1:μm
0PC	0	673 K–3.6 ks in Ar gas atmosphere	
20PA	20	673 K–3.6 ks in a salt bath	Coarse-grained Layer $f_{CGL} = 46\%$
20PB	20	673 K–60 s in a salt bath	Coarse-grained Layer $f_{CGL} = 29\%$
20PC	20	673 K–3.6 ks in Ar gas atmosphere	
20PD	20	673 K–3.6 ks in air	
50P	50	—	As-CCBent
50PA	50	673 K–3.6 ks in a salt bath	Coarse-grained Layer $f_{CGL} = 90\%$
50PB	50	673 K–60 s in a salt bath	Coarse-grained Layer $f_{CGL} = 53\%$
50PC	50	673 K–3.6 ks in Ar gas atmosphere	
50PD	50	673 K–3.6 ks in air	

The value of f_{CGL} is thickness fraction of coarse-grained layer in ND (ST direction).³⁾

using the electron backscatter diffraction pattern (EBSP) technique⁶⁾ TSL Orientation Image Microscopy (OIM) system and Philips FE-SEM.

4. Results

4.1 Changes in texture accompanying CCB process and subsequent annealing

In order to investigate changes in texture accompanying CCB process and subsequent annealing, three samples of 0P, 50P and 50PA were examined. Figure 2 shows $\{111\}$ pole figures of three layers, namely the surface, middle and center layers for the three samples. First, the pole figures for as-received specimen (0P) are analyzed (Fig. 2(a)). They represent a weak Cube texture in all three layers. There is, how-

ever, some difference among them, with regard to further details. The texture of surface and sub-surface layers has traces of a preferred orientation $\{013\}\langle 100 \rangle$, which represents the Cube texture slightly tilted about the rolling direction (RD). This texture component was observed in Al and Al alloys after rolling and after recrystallization, and is often called RD rotated Cube or Cube_{RD} .⁷⁾ The middle layer ($s = 0.5$) has a similar orientation. However, the texture of the center layer ($s = 0.0$) is the Cube texture.

After 50 CCB passes all the textures are sharper than in the as-received samples, the contour lines are denser as is illustrated in Fig. 2(b). Besides maximum value of texture strength rises slightly. The surface texture changes into stronger Cube component although some $\{013\}\langle 100 \rangle$ texture remains. A relationship between the two orientations,

(a) INITIAL Texture (0P)

(b) 50P CCB DEFORMED Texture (50P)

(c) 50P CCB RECRYSTALLIZATION Texture
(50PA, annealed at 673K for 3.6ks)

Fig. 2 The $\{111\}$ pole figures in three samples of 0P, 50P and 50PA.

$\{013\}\langle 100 \rangle$ and $\{001\}\langle 100 \rangle$ is described by rotation of 18° about $\langle 100 \rangle$ axis. In the middle layer, the CCB leads to a sharper texture, but does not produce a strong Cube orientation. In the center layer, a weak Cube texture $\{001\}\langle 100 \rangle$ changes into $\{013\}\langle 100 \rangle$. Such differences in the texture in each layer are attributed to the amount of strain and the state of constraints.

After annealing, much sharper texture appears in the surface layer (Fig. 2(c)). This is a typical Cube texture. It is found that the CCB and subsequent annealing can produce a strong Cube texture in the surface layer. On the other hand, the texture in the center is almost unchanged. As microstruc-

ture in the center layer was not given a large strain, the driving force of microstructural changes is smaller in the center than in the surface layers. In the middle layer, the texture is close to random. It is, therefore, confirmed that the textures observed in the annealed sheet are decided by those observed before annealing and to the amount of energy stored in the layers.

4.2 Development of Cube texture

The difference in texture mentioned above mainly concern the distribution of $\{hkl\}\langle 100 \rangle$. Therefore, in order to investigate the development of the Cube texture, it is more convenient to describe the texture by plotting the intensity $f(g)$ of $\{hkl\}\langle 100 \rangle$ as a function of Φ at $\varphi_1 = 0^\circ$ and $\varphi_2 = 0^\circ$ section.

These distributions are plotted in Fig. 3. The as-received sample (0P) has a weak Cube component in all three layers as shown in Fig. 3(a). Intensity of Cube texture is the strongest in the center ($s = 0.0$) layer. All of them have a small peak near $\{013\}\langle 100 \rangle$, which is consistent with the results presented in the pole figures. A sharpening of Cube texture after CCB (50P, Fig. 3(b)) is observed. The Cube texture intensity is highest in the surface, which corresponds to a large amount of strain. This fact supports the observation that the CCB process contributes to the sharpening of the Cube texture.

After annealing, a remarkable strengthening of the Cube component is observed at the surface layer as shown in Figs. 3(c) (50PA) and (d) (50PB) for the 50 pass CCB samples. Comparing Figs. 3(c) and (d), no significant difference in the texture of the surface layer is observed between annealing at 3.6 ks and 60 s at 673 K. The microstructural evolution at 673 K in the surface layer is finished after 60 s. In the middle layer a slight difference in the texture observed for these two annealing times is observed. This difference shows that some microstructural changes take place in the middle layer where a small amount of energy is stored. Similar distributions of intensity for both annealing conditions are observed in the center layer where the driving force is small. For 20 pass CCB samples (Figs. 3(e) and (f)), the development of Cube component is observed in the surface layer similarly as in the 50-pass sample. However, the Cube texture intensity is lower. Moreover, a difference in texture caused by differences in annealing time seems to be significant. Some difference is also found in the middle layer. Intensity distribution is almost unchanged in the center layer. The obtained results lead to the conclusion that the texture intensity in each layer of annealed samples after 50 or 20 CCB passes is related to the amount of stored energy or strain and to the annealing time.

4.3 Effect of annealing condition on textural change

All annealing treatments of samples were done in a salt bath. Comparisons between different annealing conditions are interesting from the viewpoint of control of texture. Our measurements demonstrated that the texture of the as-received samples does not change (See Fig. 2(a); $s = 1.0$) after annealing in Ar. This result indicates that the as-received samples have no stored energy required for nucleation and growth of the Cube component. Figure 4 shows $\{111\}$ pole figures of the surface layer ($s = 1.0$) for samples annealed in the salt bath, in Ar and in air. For the 50-pass CCBent sample, strong Cube textures are obtained by annealing both in

(a) ITAIL TEXTURE (0P)

(b) 50 CCB DEFORMED TEXTURE (50P)

(c) 50 CCB RECRYSTALLIZED TEXTURE

(50PA, annealed at 673K for 3.6ks)

(d) 50 CCB RECRYSTALLIZED TEXTURE

(50PB, annealed at 673K for 60s)

Ar and in air (50PC and 50PD, Figs. 4(e) and (f)) as well as in the salt bath (Fig. 4(d)). On the other hand, the random textures are observed for the 20-pass sample annealed both in Ar and in air (Figs. 4(b) and (c)). Such a significant difference in the textures obtained by annealing in the salt bath and in Ar or in air may be attributed to oxidation of the surface and differences in the heating rate.

Consequently, the obtained results reveal that 50 and 20

pass CCB specimens have a significant difference in the strength of the Cube texture even though they have a similar hardness (or stored energy) at the surface before annealing.³⁾

5. Discussion

5.1 Sharpening of Cube texture

In order to discuss a mechanism of sharpening of the Cube

(e) 20 CCB RECRYSTALLIZED TEXTURE

(20PA, annealed at 673K for 3.6ks)

(f) 20 CCB RECRYSTALLIZED TEXTURE

(20PB, annealed at 673K for 60s)

Fig. 3 The intensity distributions $f(g)$ of $\{hkl\}\langle 100 \rangle$ at $\varphi_1 = 0^\circ$ and $\varphi_2 = 0^\circ$ section.

texture during the CCB process and the subsequent annealing, the three samples of 0P, 50P and 50PA (corresponding to Fig. 2) were analyzed by the SEM/EBSP technique. Quantitative data for grain orientation distribution can be obtained directly from the EBSP analysis. Figure 5 shows the inverse pole figure maps for the normal direction ND for the three samples. It is difficult to compare the results obtained from this measurement in a statistical sense, because the number of grains analyzed is too small, however the non-deformed sample (Fig. 5(a)) has somehow larger grain size than severely deformed one (Fig. 5(b)) because the OIM identify the misorientations developed in deformed grains as new grain boundaries. The annealed sample (Fig. 5(c)) has more than five times larger grain size due to recrystallization and grain growth after CCB processing. It seems to have more near- $\langle 001 \rangle$ directions (red colored) than the other specimens, which observation agree with X-ray diffraction texture measurements.

Using the OIM data area fraction of a certain orientation can be obtained easily. We calculated the area fraction of pixels within an angle of deviation from $\langle 100 \rangle$ direction to ND, RD or TD. Normalization of the area fraction by expected frequency for a random texture is necessary to describe the sharpening of the Cube texture more distinctly. The expected frequency f_{exp} in the angle range of $[0, \theta]$ is derived as

$$f_{\text{exp}} = 2\pi \int_0^\theta \sin \phi d\phi / (4\pi/6) \\ = 3(1 - \cos \theta), \quad (\text{for } 0 < \theta \leq \pi/4) \quad (2)$$

from calculating area fraction of a corresponding surface area

on unit sphere in consideration of six equivalent directions of $\langle 100 \rangle$.

To illustrate differences in Cube texture the normalized cumulative area fraction in the angle range of $[0, \theta]$ for the three samples is plotted in Fig. 6. The clustering of $\langle 100 \rangle$ direction around RD is particularly strong for the annealed sample (50PA). The concentration of these directions within the range of 5° from RD is about seven times higher than for the random texture. For ND plot, the normalized fraction for an angle higher than 5° is higher for CCB and the annealed specimens. In contrast, the distribution of $\langle 100 \rangle$ directions around TD direction is scattered. Therefore, as a result of CCB and annealing the $\langle 100 \rangle$ directions are more closely aligned in ND and RD than in the TD direction.

5.2 Effect of annealing condition on texture

As mentioned above, there was a significant difference in texture obtained in different annealing conditions and also between 20P and 50P samples. While for 50P sample a sharp Cube texture developed at all three annealing atmospheres, for 20P sample the random texture is observed after annealing both in Ar and in air although the Cube texture developed during salt-bath annealing.

To obtain additional information about texture transformation the as-received sample, 0P and two CCBent samples of 20P and 50P were investigated using *in-situ* annealing in high temperature X-ray diffraction system. The changes of intensity of $\{200\}$ X-ray diffraction line were registered during heating in Ar atmosphere. The increase of intensity of $\{200\}$ line illustrates the sharpening of the Cube texture. The measurement test involved 10 measurements at given temper-

Fig. 4 The {111} pole figures of samples annealed in salt bath, in Ar and in air after the CCB.

22.50 μm = 45 steps

(a) As-received sample (0P)

35.00 μm = 70 steps Boundary levels: 5.0° 15.0°
IPF Map [001]

(b) 50 CCBent sample (50P)

40.00 μm = 20 steps

(c) Annealed sample (50PA)

Fig. 5 Inverse pole figure maps for 0P, 50P and 50PA. (CSL boundaries [$\Sigma \leq 19$] are represented by red lines.)

atures during heating at a rate of 0.5 K/s, from room temperature to 778 K. Each measurement was carried out during holding for about 350 s at each temperature.

Figure 7 shows changes in the maximum and integrated intensities of {200} peak during the heating of the 0P, 20P and 50P samples. It is known that the 0P sample has already a weak Cube texture. Both intensities remain almost constant, except that they increase slightly at about 650 K. This slight increase means that the development of Cube texture starts at about 673 K. For the 20P, no texture is formed after annealing in Ar. As shown in Fig. 7, the intensities are unchanged with the increase of temperature, until a remarkable reduc-

tion is observed at about 600 K. The reduction means that the recrystallization occurs, and then the texture is randomized at 600 K. This observation agrees with the pole figure of the sample annealed in Ar for 3.6 ks at 673 K (Figs. 4(b)(e)). In contrast to the 20P, the 50P shows fairly large increase in the intensities at about 550 K. This reveals that the annealing in Ar sharpens the Cube texture for 50P, and moreover, the sharpening takes place at a lower temperature than the transformation of texture in 20P specimen. It is notable that the increase in intensities of Cube texture was found even for the 20P after annealing in the salt-bath (Figs. 3(e)(f) and Fig. 4(a)).

Fig. 6 Concentration of cube texture in each sample direction.

To understand a role of annealing conditions on differences in texture between the 50P and 20P samples, the difference in the Cube nucleation mechanism need to be considered. One can assume that Cube nuclei in the 50 pass and 20 pass CCBent samples are surrounded respectively by the region with a high and a low dislocation density. If the Cube nuclei are surrounded by the region with a high dislocation density it can grow fast and consume the deformed matrix in the 50P sample. For the 20P sample, the growth rate of the Cube nuclei is not as fast and it is possible that more randomly oriented enter the competition.

The lack of texture for the 20P after annealing in Ar is most may be related to the PSN. This process often generates randomly oriented nucleation sites. However, large ($> 1 \mu\text{m}$) second-phase particles that stimulate PSN have not been observed in the present alloy.³⁾ It is possible that, the prior strain may reduce the size of particle required for PSN.⁸⁾ We need further study on nucleation of the Cube texture in CCB aluminum alloys to understand completely the difference between recrystallization of 20P and 50P samples.

6. Summary

In the present study, changes in texture after the CCB and the subsequent annealing of the Al-4.7mass%Mg-0.7mass%Mn alloy have been investigated. It is found that Cube texture in the surface layer is sharpened remarkably during the CCB process and the annealing that follows. After the 50 CCB passes all the textures are sharper than those obtained for as-received samples. The EBSD analysis indicates that after the CCB and the subsequent annealing, the Cube texture orientation alignment with respect to RD and ND is not the

Fig. 7 In-situ measurement of X-ray intensity during heating in a 5083 Al alloy.

same. During CCB deformation the surface texture changes into distinct Cube component, while in the middle and center layers the CCB is responsible for the sharpening of texture, but does not produce the Cube orientation. After annealing of the CCB specimens the remarkable development of the Cube component is observed in the surface layer for the 50 pass CCBent samples. In the specimen obtained for 20 passes of CCB, the Cube texture appears after annealing in a salt bath, while no texture is observed after annealing in Ar and in air.

Consequently, it is demonstrated that the CCB process enables to produce the strong Cube texture only in the surface layer of the sheet.

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