Stability of \{4 4 11\} \{11 11 8\} Orientation in a \{123\} \{634\} Aluminum Single Crystal Processed by Accumulative Roll Bonding

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A pure aluminum single crystal with a (213) [364] orientation was deformed by accumulative roll bonding (ARB) to an equivalent strain of 7.18 under lubricated conditions. The main orientation of the texture in the center layer was (4 4 11) [11 11 8]. Two different kinds of crystal rotations were observed to form (4 4 11) [11 11 8], one was the rotation from (213) [364] to (4 4 11) [11 11 8] in the center layer, and the other was the rotation from (116) [331] to (4 4 11) [11 11 8] when the area changed its position from the surface to the center. The latter rotation is followed by the cyclic ratcheting mechanism proposed by Heason \textit{et al.} These crystal rotations lead to the stable existence of the (4 4 11) [11 11 8] orientation after many ARB cycles. In the present study using the (213) [364] single crystal, the (4 4 11) [11 11 8] orientation was barely found even after an equivalent strain of 7.18. The lack of (4 4 11) [11 11 8] orientation in the center layer is due to the absence of the (001) [110] orientation in the lower surface layer. [\textit{doi:10.2320/matertrans.L-M2014833}]

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1. Introduction

Accumulative roll bonding (ARB) is a severe plastic deformation process that is capable of enhancing mechanical properties through grain refinement.\textsuperscript{1,2} This process generates through-thickness gradients in the microstructures and textures of the sheets due to the imposition of redundant shears on the sheet surfaces, which depends on the process conditions.\textsuperscript{3,4}

Heason \textit{et al.} examined the deformation textures developed in the center and surface layers of an ARB-processed AA1100 aluminum, and these textures were compared with those predicted by the full-constraints (FC) model.\textsuperscript{5} The FC model predicted that the β-fiber components (i.e., C \{112\} [111], S \{123\} [634], and B \{011\} [211]) orientations of the texture in the center layer rotated toward the \{001\} [110] orientation by redundant shear deformation when this layer changed its position toward the surface during the ARB cycles. In contrast, the \{001\} [110] orientation of the texture in the surface layer rotated toward the C orientation by one ARB cycle through plane-strain compression when this surface layer changed its position into the center in the following ARB cycle. This C orientation again rotated toward \{001\} [110] as it subsequently moved to the surface. This repeated orientation change between the surface and center layers during ARB was termed “cyclic ratcheting.”\textsuperscript{3}

Cyclic ratcheting during ARB in pure polycrystalline aluminum was also reported by Kamikawa \textit{et al.}.\textsuperscript{6} When the surface layer having a shear texture involving \{001\} [110] and \{111\} [211] components moved into the center in the following ARB cycle, the orientations were converted into \{112\} [111] and \{123\} [634] β-fiber components. Conversely, after the center layer with the β-fiber components moved into the quarter thickness, these components rotated toward the shear texture components.

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In our previous studies,\textsuperscript{7,8} \{112\} [111] and \{001\} [100] oriented aluminum single crystals were deformed up to a total reduction in thickness of 99.8% (an equivalent strain of 7.18) by conventional rolling and subsequent ARB. Both single crystals indicated that the resultant main texture components in the center layer were D \{4 4 11\} [11 11 8] orientation (Dillamore orientation). In the \{112\} [111] single crystal,\textsuperscript{7} the formation of D orientation was caused by the cyclic ratcheting reported by Heason \textit{et al.}.\textsuperscript{9} However, cyclic ratcheting barely occur in the \{001\} [100] single crystal.\textsuperscript{5} Therefore, further ARB experiments using other single crystals with different initial orientations are required in order to have a better understanding of the occurrence of cyclic ratcheting.

The aim of this study is to examine the evolution of D orientation in a (213) [364] oriented aluminum single crystal deformed by ARB. The (213) [364] single crystal has a different crystallographic character from the (112) [111] and (001) [100] crystals; the (213) [364] orientation is asymmetric with respect to the rolling direction, whereas the (112) [111] and (001) [100] orientations are symmetric. The effect of cyclic ratcheting on the stability of D orientation during ARB process is also discussed through comparing with the results obtained in the (112) [111] and (001) [100] single crystals ARB-processed in the previous studies.\textsuperscript{7,8}

2. Experimental Procedure

A (213) [364] oriented single crystal was fabricated from a 99.99% aluminum ingot using the modified Bridgman method. The initial orientation of the single crystal in Bunge’s expression was \(\phi_1 = 240.0^\circ\), \(\Phi = 36.3^\circ\), \(\phi_2 = 61.5^\circ\). The specimens cut from the original single crystal had dimensions of 4 mm \(\times\) 16 mm \(\times\) 60 mm.

The active slip systems among the twelve possible ones were analyzed using the FC model.\textsuperscript{9,10} The shear strain increments (\(\text{dy}^s\)) for slip systems (s) indicate the slip activities. The designation of the slip systems is based on notation proposed by Bishop and Hill: The letters “a” through

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“d” and numbers “1” through “6” indicate the [111] slip planes and (110) slip directions, respectively.

Table 1 shows the shear strain increment ratios (dy*/dy*j) of each active slip system for the d3 slip system obtained from the full-constraints (FC) model. For the (213) [364] orientation, the primary slip system becomes d3 while the a1, a2, c3, and d1 slip systems are also active. The shear strain increment ratios for (112) [111], (4 4 11) [11 11 8], and (116) [331] orientations are also calculated as shown in Table 1, because we deal with the crystal rotations for these crystal orientations in the following result and discussion sections. The active slip systems for (112) [111], (4 4 11) [11 11 8], and (116) [331] orientations are estimated to be a1, a2, c3, and d3. In this study, (4 4 11) [11 11 8] and (4 4 11) [11 11 8] are called D− and D+, respectively. D (4 4 11) [11 11 8] consists of the D− and D+ orientations.

According to Liu et al., the distortions associated with shear amplitude increments (dy*) on the various slip systems are specified by the distortion increment tensor (dβij)(12)

\[ dβ_{ij} = \sum_s m_{ij}^s \cdot dy^s \] (1)

where \( m_{ij}^s = (C_i \cdot b^s)(C_j \cdot n^s) \) is the generalized Schmid factor tensor; \( C_i \) and \( C_j \) are ith and jth basis vectors in the specimen coordinate system, respectively. In this study, axes 1, 2 and 3 in the specimen coordinate system are parallel to the rolling direction (RD), transverse direction (TD), and normal direction (ND), respectively. \( b^s \) and \( n^s \) are the slip direction and slip plane normal, respectively.

In the FC model, the three components of crystal rotation increment are given as(12)

\[ dR = [dR_{11}, dR_{22}, dR_{33}] = [-dβ_{32}, dβ_{31}, -dβ_{21}] \] (2)

Since this study mainly focuses on the crystal rotation about the TD axis, the crystal rotation increments (dR) about the TD axis were dealt with, and the directions of crystal rotations were shown in Table 2.

The directions of clockwise (+) and counterclockwise (−) rotations about the TD axis were indicated by arrows in Fig. 1. For the (112) [111] orientation, the crystal rotates clockwise about the TD axis relative to the original orientation. Therefore, the (112) [111] crystal rotates toward D− orientation (Table 2). For the (116) [331] orientation, the crystal rotates counterclockwise about the TD axis toward D+ orientation. The crystal rotation for the (213) [364] orientation includes rotation components about all the RD, TD, and ND axes; the direction of rotation about the TD axis is clockwise.

Table 2 shows the total thickness reduction (r) and the equivalent strain (e) imposed on the specimen by rolling and ARB. The single crystal specimens were deformed using a two-high rolling mill (diameter of the rolls: 310 mm) at room temperature with lubrication. Firstly, one-pass rolling with 50% reduction in thickness was applied twice to the original single crystal with 4 mm thickness, making the thickness of the single crystal sheet 1 mm (75% reduction in thickness). Then, the ARB process using 50% reduction in thickness was conducted. The method of stacking sheets cut in the ARB process was illustrated in Fig. 1. In the present ARB process, the 1 mm sheet was cut into two (named sheets I and II), and then the specimen was cooled in water immediately after rolling.
where $h_0$ and $h_1$ are the thicknesses of the specimen before and after rolling (ARB), respectively. Electron backscatter diffraction (EBSD) measurements were performed at a step size of 1 µm using a field-emission scanning electron microscope (FEI XL-30S). The observation area (width: 250 µm; thickness: 1000 µm) was perpendicular to the TD axis and is hereafter referred to as the TD plane. The area fractions of the major crystal orientations throughout the specimen thickness were determined from the EBSD data using TSL-OIM analysis ver. 5.0 software. The tolerance value for classifying each orientation area was 10°. The textures at three different locations through the thickness were also examined. The thickness location ($X$) is defined in terms of the specimen thickness ($t$): $X = 0t$ and $X = 1t$ correspond to the upper and lower surfaces, respectively, while the layers at $X = 0t - 0.25t$, $X = 0.25t - 0.75t$, and $X = 0.75t - 1t$ are referred to as the upper surface layer, center layer, and lower surface layer, respectively.

3. Experimental Results

Figure 2 shows the changes in the area fractions of the major crystal orientations during processing. In the range of equivalent strain from 2.4 (three ARB cycles) to 4 (five ARB cycles), the area fraction of the $D^-$ (4 4 11) [1 1 1 8] orientation dramatically increased, while that of the original (213) [364] orientation decreased. The area fractions of the (213) [364], $D^-$, (001) [110], and (111) [112] orientations at an equivalent strain of 7.18 (nine ARB cycles) were 2.5%, 27.6%, 5.8%, and 1.4%, respectively. The area fraction of the $D^+$ (4 4 11) [1 1 1 8] orientation after the ninth cycle was only 1.9%. The previous study using the (112) [111] single crystal revealed the area fraction of the $D^+$ orientation to be 12.7%; comparison of these results reveals a significant difference in the formation of the $D^+$ orientation.

Figure 3 shows (111) pole figures in the three different layers after the third, fifth, seventh, and ninth ARB cycles. The maximum pole intensities ($I_{max}$) of the texture components decreased with increasing the number of ARB cycles. One of the reasons is due to complicated strain paths, namely plane-strain compression on the center layer and redundant
shear on the surface layer, are repeatedly imposed on the specimen during ARB.6)

The textures in the center layer indicate continuous crystal rotation from (213) [364] to D− (Figs. 3(e) to (h)). After the ninth ARB cycle, the deformation texture is characterized by the development of D− component with the highest pole intensity of 12.4. However, the D+ component did not develop significantly and its pole intensity was lower than 2° (Fig. 3(h)).

In the lower surface layer, continuous crystal rotation from (213) [364] to (116) [332] was observed (Figs. 3(i) to (l)), and (116) [332] became a main component of the texture. Geometrically, the (116) [332] orientation was obtained by 14° of clockwise rotation about the TD axis with respect to the D+ orientation.

The upper surface layer after the ninth cycle showed a broad distribution of texture components ranging from (001) [110] to (111) [112] (Fig. 3(d)).

Figure 4 shows crystal orientation maps on the TD plane. The yellow color indicates (213) [364] (Fig. 3(h)). In the lower surface layer, continuous crystal rotation from (213) [364] to (116) [332] was observed (Figs. 3(i) to (l)), and (116) [332] became a main component of the texture. Geometrically, the (116) [332] orientation was obtained by 14° of clockwise rotation about the TD axis with respect to the D+ orientation.

The upper surface layer after the ninth cycle showed a broad distribution of texture components ranging from (001) [110] to (111) [112] (Fig. 3(d)).

Figure 4 shows crystal orientation maps on the TD plane. The yellow color indicates (213) [364] orientation. The D−, D+, (001) [110], and (111) [112] areas are depicted by blue, green, red, and pink, respectively. In Fig. 4(a), the upper half of the specimen (X = 0t − 0.5t) after the third ARB cycle is defined as section 3A and the lower half (X = 0.5t − 1t) is defined as section 3B. Section 3B consisted of a half of the center layer (X = 0.5t − 0.75t) and the lower surface layer (X = 0.75t − 1t). The letters 4A through 4D were assigned to each of the four sections from the top to the bottom of the specimen after the fourth ARB cycle (Fig. 4(b)). Sections 4A (X = 0t − 0.25t) and 4D (X = 0.75t − 1t) corresponded to the upper and lower surface layers, respectively, and sections 4B and 4C (X = 0.25t − 0.75t) the center layer. In Fig. 4(c), the eight sections of the specimen after the fifth ARB cycle were labeled 5A through 5H. Sections 5A and 5B (X = 0t − 0.25t), and sections 5G and 5H (X = 0.75t − 1t) were regarded as the upper and lower surface layers, respectively, and sections ranging from 5C to 5F (X = 0.25t − 0.75t) became the center layer.

The change in crystal orientations between two areas, which stayed in the center layer through two ARB cycles, was examined. The first example is about the change in crystal orientations between section 4B after the fourth cycle and section 5F after the fifth cycle. Section 4B was composed of (213) [364] and D− oriented areas that were shown as yellow and blue, respectively (Fig. 4(b)). By cutting and stacking in the following ARB cycle, section 4B was split into sections 5B and 5F (Fig. 4(c)). Comparison of section 4B with section 5F reveals that the yellow area, i.e., (213) [364] oriented area, in section 4B was converted into a blue area, i.e., D− oriented area, in section 5F. In the second example on sections 4C and 5C (Figs. 4(b) and (c)), section 4C was composed of yellow and blue areas with some red. When section 4C changed its position into section 5C in the next ARB cycle, the yellow area in section 4C was converted into mostly blue area with some remnant yellow in section 5C. Thus, the crystal rotation from (213) [364] (yellow) to D− (blue) was observed between the areas which were located in the center layer through two ARB cycles.

Next, we examined the change in orientations between two areas, when an area was transferred from the lower surface to the center. The first example is about the change in orientations between section 3B after the third cycle and section 4B after the fourth cycle (Figs. 4(a) and (b)). When section 3B moved into section 4B, the red area near the surface (X = 0.8t − 1t) in section 3B was converted into blue area in section 4B. It indicates that the crystal rotation from (001) [110] to D− occurred by one ARB cycle. In the second example, when section 4D after the fourth cycle changed its position into section 5D in the next cycle, the red area, i.e., (001) [110] oriented area, in section 4D changed into blue

![Crystal orientation maps of the ARB-processed specimens measured by EBSD on the TD planes. The colors in these maps indicate deformation areas with orientations within 10° from the ideal (213) [364], D− (4 4 11) [11 11 8], D+ (4 4 11) [11 11 8], (001) [110], and (111) [112] orientations.](image-url)
area, i.e., D-oriented area in section 5D (Figs. 4(b) and (c)). Thus, it is evident that the (001) [110] oriented area was converted into D-oriented area after the lower surface layer changed its location into the center in the next ARB cycle.

Here, we must note that in Fig. 4(e), the red area in the lower surface layer after the ninth cycle was regarded as the (001) [110] oriented area; however, in Fig. 3(i), the main component of the texture is indexed as the (116) [331] orientation, which is intermediate of (001) [110] and D-orientations. In this study, the main orientation of the texture in the lower surface layer after ninth cycle was identified as (116) [331].

4. Discussion

4.1 Occurrence of cyclic ratcheting in (213) [364] single crystal

The textures in the center layers between the third and ninth cycles showed a continuous crystal rotation from the initial (213) [364] orientation to D- (4 4 11) [11 11 8] (Figs. 3(e) to (h)), whereas the textures in the lower surface layers showed a continuous crystal rotation from (213) [364] to (116) [331] orientation (Figs. 3(i) to (l)).

Based on the results shown in Fig. 4, the D- orientation in the center layer is formed via two different strain paths. The first strain path is imposed on an area when it stays in the center layer through two ARB cycles; for example, the strain path at sections 4B and 5F caused the continuous crystal rotation from (213) [364] to D- orientations (Figs. 4(b) and (c)). The second strain path is imposed on an area when it moves from the lower surface to the center through two ARB cycles; for example, the strain path at sections 4D and 5D leads to the quick crystal rotation from (001) [110] to D-orientations by one ARB. These crystal rotations, which result from different strain paths, are considered to be the reason for the stable existence of the D- orientation even after many ARB cycles that include cutting, stacking, and rolling processes. In particular, the crystal rotation in the second strain path is regarded as the rotation caused by “cyclic ratcheting”.5

The occurrence of cyclic ratcheting was first reported by Heason et al.,5 and second by Kamikawa et al.,6 and more recently by Li et al.14 According to their reports, an area that moves from the surface to the center during ARB shows crystal rotation about the TD axis from [001] (110) to [112] (111)5,6 or to {4 4 11} (11 11 8).14

The crystal rotation from [001] (110) (or [116] (331)) to D orientation caused by cyclic ratcheting was observed in the present study using the (213) [364] single crystal and in one of our previous studies using the (112) [111] single crystal.7 However, only a small amount of cyclic ratcheting was observed in the other previous study using the (001) [100] single crystal.9 The area fraction of [001] (110) was 5.8% in the (213) [364] single crystal and 6.3% in the (112) [111] single crystal,7 whereas it was only 0.2% in the (001) [100] single crystal.9 The (213) [364] and (112) [111] single crystals showed the obvious crystal rotation from [001] (110) (or [116] (331)) to D orientation. In contrast, in the (001) [100] single crystal, the crystal rotation from [001] (110) to D orientation hardly occurred. Thus, the formation of [001] (110) (or [116] (331)) orientation, especially when formed in the surface layer, is important for the occurrence of cyclic ratcheting, which depends on the initial crystal orientations. In the next section, we discuss the formation of D- and D+ orientations (or the variant selection of D orientation) caused by cyclic ratcheting.


After the ninth cycle, the deformation texture in the center layer developed D- (4 4 11) [11 11 8] component with the highest pole intensity of 12.4. However, the D+ (4 4 11) [11 11 8] component did not develop significantly and its pole intensity was lower than 2 (Fig. 3(h)). In one of our previous studies using the (112) [111] single crystal,7 the deformation texture in the center layer after the ninth cycle included both D- and D+ components with pole intensities of 7 and 4.4, respectively.

After the ninth cycle, the area fraction of the D+ orientation throughout the thickness was 1.9% in the present study and 12.7% in the previous study.7 There was a significant difference in the development of the D+ component between the (213) [364] and (112) [111] single crystals.

Figure 5 shows (111) octahedrons models depicting the crystal orientations in the lower surface layer after the seventh cycle and the center layer after the ninth cycle in the (213) [364] single crystal (a)–(c)) and the (112) [111] single crystals ((d)–(f)), respectively.
orientation (Fig. 5(c)). The (001) [110] orientation is known to be unstable during deformation under the plane-strain compression condition\textsuperscript{15,16} Therefore, when a (001) [110] oriented area in the lower surface layer moves to the center in the next ARB cycle, this area is split into two due to counterclockwise and clockwise rotations about the TD axis toward the D− and D+ orientations (Figs. 5(c) and (f)). The counterclockwise rotation toward the D− orientation is caused by the operation of a1 and a2 slip systems, while the clockwise rotation toward the D+ orientation is caused by of the b1 and b2 slip systems.

In this study using the (213) [364] single crystal (Fig. 5(a)), the main component of the texture in the lower surface layer after the seventh cycle was the (116) [331] orientation instead of the (001) [110] orientation (Fig. 5(b)). When the (116) [331] oriented area in the surface layer changed its position into the center in the next ARB cycle, this area rotates in one direction, i.e., counterclockwise, about the TD axis toward the D− orientation (Table 2). This rotation is generated by the operation of the a1 and a2 slip systems (Fig. 5(c)). This is the reason why the (213) [364] crystal does not develop significant D+ orientation. Further ARB would be required to form (001) [110] in the lower surface layer of the (213) [364] single crystal under lubricated conditions.

The upper and lower surface layers were subjected to redundant shears during every ARB cycle. Geometrically, it was expected that the upper surface layer developed the (111) [112] orientation due to the friction between the specimen and the upper roll. A small number of (111) [112] oriented areas (pink) were observed after the fifth and ninth cycles (Fig. 4(c) and (e)). However, as shown in Fig. 2, (111) [112] orientation did not increase significantly. The (111) pole figure in the upper surface layer indicates a broad distribution of components around the TD axis ranging from (001) [110] to (111) [112] after the ninth cycle (Fig. 3(d)). The pole intensity of (111) [112] was very low. From these results, it is difficult to assess the effect of the texture components including (111) [112] orientation formed in the upper surface layer on the formation of D− and D+ orientations. The reason for the underdevelopment of (111) [112] orientation is unknown; it may be deduced from the distortions associated with shear amplitude increments in the (111) [112] orientation.

5. Conclusions

A (213) [364] oriented aluminum single crystal was deformed to an equivalent strain of 7.18 in total (99.8% reduction in thickness). Conventional rolling was carried out in the first and second cycles, and ARB was performed from the third cycle with lubrication. The following conclusions were obtained from this study:

1. The textures in the center and lower surface layers show continuous crystal rotations from the initial (213) [364] orientation to D− (4 4 11) [111 11 8] and from the initial orientation to (116) [331], respectively.
2. The stable existence of the D− orientation in the center layer even after many ARB cycles is attributed to the crystal rotations that occur via the two different strain paths: The first strain path is imposed on the area which stays in the center layer through two ARB cycles and the second strain path is imposed on the area which moves from the lower surface to the center. The crystal rotation in the second strain path is caused by cyclic ratcheting proposed by Heason et al.\textsuperscript{51}
3. The D+ (4 4 11) [111 11 8] component barely develops after the ninth cycle because the main texture component in the lower surface layer is (116) [331] orientation. The formation of the (001) [110] orientation in the lower surface layer is required to form the D+ orientation in the center layer.

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