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Cyclic transition of deformation in $\{1\ 2\ 3\}$ $\langle 6\ 3\ 4 \rangle$ single crystal processed by accumulative roll-bonding

Hui Wang

University of Wollongong, huiw@uow.edu.au

Cheng Lu

University of Wollongong, chenglu@uow.edu.au

Anh Kiet Tieu

University of Wollongong, ktieu@uow.edu.au

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Abstract

In this study, the crystal plasticity finite element method model was used to study the deformation in a single crystal aluminium processed by accumulative roll-bonding (ARB). The predicted textures match well with the experimental observations up to nine cycles. The texture and slip activities in representative layers were investigated, and cyclic transition of them was observed. It was found that the thickness position change caused by cutting and stacking was a basic reason for the cyclic transition. Finally, the effect of shear deformation to this transition was discussed.

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Cyclic transition of deformation in {1 2 3}<6 3 4>aluminum single crystal processed by accumulative roll-bonding

Hui Wang, Cheng Lu, Kiet Tieu

School of Mechanical, Materials, Mechatronic and Biomedical Engineering, University of Wollongong, Wollongong, Australia

CONTACT Hui Wang hw737@uowmail.edu.au School of Mechanical, Materials, Mechatronic and Biomedical Engineering, University of Wollongong, Wollongong, New South Wales 2522, Australia

ABSTRACT

In this study, the crystal plasticity finite element method model was used to study the deformation in a single crystal aluminum processed by accumulative roll-bonding (ARB). The predicted textures match well with the experimental observations up to nine cycles. The texture and slip activities in representative layers were investigated, and cyclic transition of them was observed. It was found that the thickness position change caused by cutting and stacking was a basic reason for the cyclic transition. Finally, the effect of shear deformation to this transition was discussed.

KEYWORDS

Accumulative roll bonding; crystal plasticity finite element method; single crystal; texture; cyclic transition; aluminium; slip activity; shear deformation

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Introduction

The accumulative roll-bonding (ARB) process involves repetitive cutting, stacking and roll-bonding. Experimental studies of ARB-processed metals have revealed a heterogeneous distribution of through thickness deformation behaviors (e.g., strain, texture, and microstructure) in a cycle [1, 2]. In the next cycle, the cutting-stacking in ARB moves the materials to different thickness locations, and then the materials experience different deformations. This difference in deformation would lead to changes in texture and microstructure between cycles, which has been widely researched [1, 2, 3]. However, how multiple ARB cycles influence the cyclic transition of texture and microstructure in particular layers has not been investigated, and this is the motivation of this study.

The experimental methods are incapable to trace the deformation history. Alternatively, texture modelling has become a powerful method, and it has been successfully applied to ARB [1, 4, 5, 6, 7, 8, 9, 10]. Based on the Taylor model, a ‘ratcheting’ mechanism has been proposed by Heason and Prangnell [4] to explain the cyclic texture transition between two texture components, $\{0\ 0\ 1\}<1\ 1\ 0>$ and $\{1\ 1\ 2\}<1\ 1\ 1>$. In the Taylor model, the deformation of grains is simply assumed to be the same as the macroscopic strain [11], and the stress equilibrium is disregarded. Homogenization at different levels is adopted in the crystal plasticity (CP) models used in Refs. [1, 4, 7], and thus local heterogeneities cannot be spatially and explicitly captured by these CP models [12]. In contrast, no homogenisation is in principle assumed in the crystal plasticity finite element method (CPFEM) model, in which the CP constitutive law is incorporated into the finite element method (FEM) framework. In this model, texture evolution and plastic deformation are fully coupled during deformation. The CPFEM model has been used to study the texture evolution in ARB-processed single crystals [8, 9], polycrystals [10], and two-phase composites [5, 6].

In this study, the CPFEM model was adopted to trace the deformation history of selected ARB layers, and then the cyclically formed and destroyed textures and cyclic changes of slip activities were investigated.

Texture modelling

ABAQUS/Standard Ver.6.9 was used to perform the simulation. The CP model in this research followed the kinematical scheme proposed by Asaro and Needleman [13, 14]. The slip plane is $\{1\ 1\ 1\}$ and slip direction is $<1\ 1\ 0>$ in FCC structured aluminum, and the 12 slip systems are listed in Table 1. The Bassani-Wu hardening model [15] was adopted, and the material parameters were evaluated by fitting the simulated stress-strain curve with the experimental results [8]. The kinematical scheme and hardening model were incorporated into ABAQUS/Standard via user-defined material (UMAT) subroutine. The framework of UMAT was initially developed by Huang [16]. The variables used in the CPFEM model were saved as solution-dependent state variables (SDV) in ABAQUS/Standard, and these variables were updated after each FEM increment. The CP constitutive law, CPFEM implementation, hardening model, and material parameters used in the simulation have been given in Ref. [8].

Table 1. Notation of slip systems.

Slip plane	$(1\ 1\ 1)$			$(\bar{1}\ \bar{1}\ 1)$			$(\bar{1}\ 1\ 1)$			$(1\ \bar{1}\ 1)$		
Slip direction	$[0\ 1\ \bar{1}]$	$[\bar{1}\ 0\ 1]$	$[1\ \bar{1}\ 0]$	$[0\ \bar{1}\ \bar{1}]$	$[1\ 0\ 1]$	$[\bar{1}\ 1\ 0]$	$[0\ 1\ \bar{1}]$	$[1\ 0\ 1]$	$[\bar{1}\ \bar{1}\ 0]$	$[0\ \bar{1}\ \bar{1}]$	$[\bar{1}\ 0\ 1]$	$[1\ 1\ 0]$
Slip system	1	2	3	4	5	6	7	8	9	10	11	12

The CPFEM simulation followed the ARB experiment in Ref. [17]. The starting material was a single crystal aluminum with a starting orientation of $(2\ 1\ 3)[3\ 6\ \bar{4}]$ (S). It was conventional rolling in 1- and 2-cycle, and ARB was applied from 3-cycle onwards [17], as the rolling procedure schematically shown in Figure 1. A two-dimensional FEM model under plane strain conditions was developed. The FEM model was given in a previous report of the authors [8]. The reduction was 50% in each cycle. Mapping solution was used between cycles to transfer the solution (or results) from the deformed mesh to a new mesh [8]. To obtain the solution at a node of the deformed mesh, the values of integration points in all elements (of the deformed mesh) having this node were extrapolated, and then the values were averaged over these elements. All necessary variables used in ABAQUS/Standard and UMAT were interpolated from the nodes of the deformed mesh to the nodes of the new mesh according to the positions of nodes (of the new mesh) in the elements of the deformed mesh. The element type was 4-node bilinear with reduced integration and hourglass control (element ID: CPE4R). The shape of elements was square in all cycles, and mesh calibration was performed. The rolls were treated as analytical rigid bodies with diameters of 310 mm. After testing a series of friction coefficients, a coefficient of 0.125 was used to describe the friction between the sheet and rolls.

Figure 1. A schematic shows the ARB simulation procedure.

Results

Validation of predictions

Figure 2(a-e) shows the simulated and experimentally observed through thickness textures, and Figure 2(f) presents the changes in area fraction of three texture components. The positions of these three texture components are expressed by a $\{1\ 1\ 1\}$ pole figure in Figure 2(g), and the crystal rotation about the transverse direction (TD) is also marked. There is only one layer after 2-cycle (Figure 2(a)), which is termed A_2 , where the subscript stands for the cycle number. The starting orientation S was destroyed at the two surfaces (Figure 2(a)). ARB was applied from 3-cycle, and then the number of layers was doubled after each single cycle owing to the cutting and stacking. The two layers in 3-cycle are termed A_3 and B_3 (Figure 2(b)). $(0\ 0\ 1)[1\ 1\ 0]$ (rotated-Cube) evolved at the lower surface (in B_3), and $(4\ 4\ 11)[11\ 11\ \bar{8}]$ (D^-) at the lower subsurface of B_3 . The predicted area fractions of these three texture components, S , D^- , and rotated-Cube after 3-cycle match well with the experimental observations (Figure 2(f)). Two 3-cycle processed sheets were stacked at the beginning of 4-cycle (Figure 2(c)). The previously formed rotated-Cube in B_3 (of 3-cycle) rotated into D^- in B_4 (of 4-cycle) after B_3 was moved to B_4 . In contrast, this texture component was preserved after B_3 being moved to D_4 . A new fraction of D^- was formed in C_4 from the formerly destroyed S in A_3 . In 4-cycle, the area fraction of D^- is close to S (Figure 2(f)). The eight layers in 5-cycle are defined as A_5 to H_5 . In Figure 2(d), D^- obviously replaced S as the major texture component, and it reached the maximum in area fraction (Figure 2(f)). This texture component dropped in area fraction after 6- and 7-cycle (Figure 2(f)), and then became almost unchanged in the following cycles. The area fraction of S decreased quickly in 5-cycle (Figure 2(d,f)), and then stayed stable afterwards. Similar to that in 4-cycle, the rotated-Cube previously evolved in D_4 remained in H_5 (of 5-cycle), while it was destroyed in D_5 and a part of it rotated into $(\bar{4}\ \bar{4}\ 11)[11\ 11\ 8]$ (D^+). After 7-cycle (Figure 2(e)), the whole thickness was divided into 32 layers. D^+ evolved at the center and quarter, and $(1\ 1\ 2)[1\ 1\ \bar{1}]$ near the upper quarter region. It can be seen from Figure 2(c-f) that the predictions agree well with the experimental observations.

Figure 2. Texture component maps through the whole thickness after (a) 2-, (b) 3-, (c) 4-, (d) 5-, and (e) 7-cycle in the simulation and experiment [17]. (f) Changes of texture components, S , D^- ,

and rotated-Cube, in area fraction. (g) A $\{1\ 1\ 1\}$ pole figure shows the positions of three texture components and TD-rotation.

A₂-A₃-A₄-A₅ and A₄-E₅ paths

Figure 2(a-e) shows that texture gradients developed through the thickness, which means the through thickness deformation was not uniform. Due to the cutting and stacking, the layers in ARB were moved into either different or the same thickness positions. In the following, the texture evolution and slip activities in representatively selected layers underwent different movement paths will be investigated.

The first investigated layers and path are A₂-A₃-A₄-A₅, by which the selected A₂ layer in 2-cycle was moved to A₃ in 3-cycle, A₄ in 4-cycle, and A₅ in 5-cycle. The texture component maps, distribution of crystal rotation angles, and shear strain on slip systems in these layers are shown in Figure 3(a,b,c), respectively. The values of rotation angles and shear strain on slip systems are those evolved in a single cycle, but not cumulated with cycles. Slip activity was used here to simply represent the microstructure owing to its importance in microstructure evolution [18]. In Figure 3(a), the crystal orientations at the two surfaces of A₂ rotated away from the starting S. The crystal rotation in (Figure 3(b)) is relatively low, and the highly activated slip systems were 1-12-9-2 (Figure 3(c) and Table 1). After A₂ was moved to A₃, the unindexed texture at the lower surface of A₂ rotated back to S in A₃ (Figure 3(a)). There is only one layer in 2-cycle (i.e., A₂) and two layers in 3-cycle (A₃ and B₃), and the lower surface of A₃ is actually the center of the whole

sheet in 3-cycle. This is to say texture reversal occurred when the lower surface of the sheet was moved to the center. The crystal rotation is also low in A₃ (Figure 3(b)), and the primarily activated slip systems were 1-2-5-9-12. The crystal orientations in A₄ and A₅ rotated away from S (Figure 3(a)), and the crystal rotation is relatively large (Figure 3(b)). The slip activities in A₄ and A₅ are similar to those in A₃. This similarity is owing to that this layer (A₃-A₄-A₅) remained at the upper surface of the sheet (Figure 2) and thus it experienced (almost) unidirectional deformation.

Figure 3. (a) Texture component maps, (b) distribution of crystal rotation angles, and (c) shear strain on slip systems in A₂, A₃, A₄, A₅, and E₅ layers.

By following the A₄-E₅ path (Figure 2), the A₄ layer (at the upper surface of 4-cycle) was also moved to E₅ (near the center of 5-cycle), and D- was developed in E₅ after A₄ being moved to E₅ (Figure 3(a)). In Figure 3(b,c), the distribution of crystal rotation and slip activities in E₅ are different from those in A₄, since A₄ and E₅ were at different thickness positions. Meanwhile, the crystal rotation and slip activities in E₅ are also different from those in A₅ though both A₅ and E₅ had the same initial conditions (mapped from A₄). These differences suggest that the deformation was altered when the layer was moved to a different thickness location, since the through-thickness deformation was not uniform.

A₂-B₃-D₄-H₅ and D₄-D₅-(L₆)-AB₇ paths

In this part, the investigated layers and paths are A₂-B₃-D₄-H₅ and D₄-D₅-(L₆)-AB₇, where L₆ is not shown in Figure 4. After A₂ was moved to B₃, the starting S was destroyed (Figure 3(a)), and it was replaced by the new developed D- and rotated-Cube in B₃ (Figure 4(a)). The development of rotated-Cube in B₃ was owing to +TD-rotation (Figure 4(b) and Figure 2(g)), but the crystal rotation is very low, where the rotation in a cycle can be seen from the spatial distance between the initial and final poles in Figure 4(b). The slip activities in B₃ (slip system 1-12-9-2-5 in Figure 4(c)) are similar to those in A₂ (Figure 3(c)). When B₃ was moved to D₄ in 4-cycle, the starting S was further destroyed (Figure 4(a)), which was caused by both +TD-rotation and -TD-rotation (Figure 4(b)). The large change of crystal orientations in Figure 4(b) means the destruction of S was quick. The slip activities in D₄ are similar to those in B₃, since they both were located at the lower surface of the whole sheet (Figure 2). After D₄ was moved to H₅ in 5-cycle, the texture component rotated-Cube increased in area fraction by replaced D-, and both +TD-rotation and -TD-rotation developed in the destroyed D- (Figure 4(b)). The slip activities in H₅ are similar to those in D₄ (Figure 4(c)), since H₅ was also located at the lower surface of 5-cycle.

Figure 4. (a) Texture components maps, and (c) shear strain on slip systems in B₃, D₄, H₅, D₅, and AB₇ layers. (b) {1 1 1} pole figures show the crystal orientations before (black) and after (red) a cycle of selected texture components.

As for the D_4 - D_5 -(L_6)- AB_7 path, the D_4 layer (of 4-cycle) can also be moved to AB_7 (of 7-cycle). When D_4 (at the lower surface of the sheet) was transferred to D_5 (near the center), the area fraction of rotated-Cube decreased greatly in D_5 layer (Figure 4(a)), and only an extremely low fraction remained. The destruction of rotated-Cube was quick (Figure 4(b)), and was owing to both +TD-rotation and -TD-rotation. It is interesting that the S component developed in D_4 was well preserved in D_5 . The slip activities in D_5 (slip system 1-2 in Figure 4(c)) are quite different from those in D_4 . The D_5 layer was moved outwards to the lower surface by following the D_4 - D_5 -(L_6)- AB_7 path. The destroyed rotated-Cube in D_5 reappeared in AB_7 (Figure 4(a)), and this reappearance was owing to low +TD-rotation (Figure 4(b)). The slip activities in AB_7 were also altered from D_5 , since D_5 and AB_7 were located at different thickness positions (Figure 2(d,e)). However, the slip activities in AB_7 (slip system 1-12-9-5-2) are similar to those in H_5 and D_4 , since all these three layers were located at or near the lower surface of the sheet. The previously activated slip systems, 9-12, in D_4 became almost inactive in D_5 , and then they were reactivated again in AB_7 , i.e., cyclic transition of slip activities.

Effect of surface friction

To match the lubricated ARB experiment in Ref. [17], a small friction coefficient (0.125) was used in the above simulation, and this is why the developed shear texture (i.e., rotated-Cube) is very low in area fraction (Figure 2(f)). In contrast, shear texture develops even at the quarter thickness when the surface friction is very high [19]. Surface friction is one important contributor to the shear deformation during rolling, and it has been found that the surface friction induced shear deformation plays a key role in the distribution and fraction of shear textures [2, 20]. To investigate the influence of surface friction to the cyclic transition of texture and slip activities, another two simulations with friction coefficients of 0.15 and 0.1 were conducted, where the former and later coefficient is respectively higher and lower than that used in Figure 2-4. The simulation results with these two coefficients are shown in Figure 5, and the selected layers and path are A_2 - B_3 - D_4 - D_5 .

Figure 5. Texture components maps and shear strain on slip systems in A₂, B₃, D₄, and D₅ layers with friction coefficients of (a, b) 0.15, and (c, d) 0.1.

When the friction coefficient was increased to 0.15 (Figure 5(a)), rotated-Cube started to develop in A₂ (2-cycle), while it formed in 3-cycle when the friction coefficient was 0.125 (Figure 4(a)). In Figure 5(a), the area fraction of rotated-Cube increased in B₃ and D₄, and it is higher than those in their counterparts in Figure 4(a). The faster evolution and higher fraction of shear texture in Figure 5(a) suggest that the higher friction coefficient benefited to the formation of shear texture. The shear texture developed in D₄ was destroyed in D₅ (Figure 5(a)) when D₄ (at the lower surface of 4-cycle) was moved to D₅ (at the center of 5-cycle). The destroyed shear texture in D₅ evolved into unindexed texture components, which is different from the destruction of shear texture in this layer with the friction coefficient of 0.125 (Figure 4(a)). The slip activities in A₂, B₃, and D₄ are similar (slip system 1-12-9) owing to no change in thickness position, and they are also similar to those with the friction coefficient of 0.125. However, the activated slip systems were altered to 1-5-4 when D₄ was moved to the sheet center (i.e., D₅). The slip activities in D₅ are also different

from those (slip system 1-2) in its counterpart with the friction coefficient of 0.125 (D_5 in Figure 4(c)).

Shear texture did not develop even after 5-cycle when the friction coefficient was reduced to 0.1, as can be seen from Figure 5(c). The area fraction of D- increased gradually with increasing cycles (A_2 , B_3 , D_4 , and D_5 layers), which means texture transition did not occur when D_4 was moved to D_5 . The slip activities (slip system 1-2-9-12) in D_5 are similar to those in A_2 , B_3 , and D_4 though they were at different thickness positions. This is to say the change in thickness position did not alter slip activities when the friction coefficient is 0.1.

Discussion

The ARB process involves repetitive cutting-stacking, and accordingly the thickness positions of layers change cyclically. When the layers were moved to different positions, the deformation in the layers was altered, since the through-thickness deformation was non-uniform even though the friction coefficient in this study was only 0.125. In contrast, the lower friction coefficient, 0.1, did not cause the cyclic transition, which means the shear deformation in this case is very small. It has been seen that large shear deformation due to high surface friction resulted in a higher fraction of shear texture (i.e., friction coefficient 0.15), and the large shear deformation also influences the cyclic transition of texture and slip activities. A general and ideal model is shown in Figure 6 to explain the cyclic transition of texture in ARB, and also the influence of shear deformation (associated with shear texture fraction) to this cyclic transition. In this model, the distribution of shear texture and rolling texture is the same after each cycle. The thickness position t is defined as $t=0$ and 1 corresponding to the upper and low surfaces, respectively. The shear deformation is assumed to be high in Figure 6(a), and this results in a large fraction of shear texture at the surfaces ($t=0-0.25$, and $0.75-1$), while the low shear deformation in Figure 6(b) gives rise to a small fraction of shear texture ($t=0-0.125$, and $0.875-1$). It is rolling texture in the inner region, $t=0.25-0.75$ in Figure 6(a) and $0.125-0.875$ in Figure 6(b).

Figure 6. Distribution of textures with a (a) large, and (b) small area fraction of shear texture.

In Figure 6(a), shear texture and rolling texture form in 1-cycle. In the following cycles, 50% of the sheet thickness in Figure 6(a) experiences texture transition between rolling texture and shear texture after each single cycle, while only 25% in Figure 6(b). In 2- to 4-cycle of Figure 6(a), shear texture forms at the subsurface, and this occurs when the material is moved outwards to the surfaces. The subsurface involves a relatively small change in thickness position, and in the present study this small change resulted in low crystal rotation [21], e.g., the formation of rotated-Cube in B_3 and AB_7 of Figure 4(b). In contrast, rolling texture forms at the center (Figure 6(a)), and this formation is accompanied by the destruction of shear texture. Rolling texture formation, or destruction of shear texture, involves a large change in thickness location (from the surfaces to the center), and this large change results in high crystal rotation (E_5 in Figure 3(b) and D_5 in Figure 4(b)). The rapid formation of rolling texture has been reported in Refs. [3, 21].

The red arrows in Figure 6(a) show the path of shear texture reformation. By following this path only three cycles are needed for the reappearance of shear texture. In contrast, four cycles are required in Figure 6(b) (also marked by red arrows). Though this layer movement path in Figure 6(a) is similar to that in Figure 6(b), i.e., from the upper surface to lower surface, it is obvious that

more cycles are needed for shear texture to redevelop when the fraction of shear texture is lower. The path indicated by green arrows in Figure 6(a) shows the shear texture reformation at the same position, e.g., from the lower surface to lower surface, and four cycles are needed in this case. In Figure 6(a), three cycles are needed for the reformation of rolling texture by following the path marked by blue arrows. Similarly, three cycles (marked by blue arrows) are required for the reappearance of rolling texture in Figure 6(b). The thickness position of layers changes cyclically after multiple ARB cycles, and this is a basic reason for cyclic transition of texture and slip activities in ARB.

Conclusions

1. A CPFEM simulation was conducted to study the texture evolution and slip activities in an ARB-processed aluminum single crystal, and the predictions match well with the experimental observations.
2. It was found that the deformation, in terms of texture evolution and slip activities, was almost unidirectional if the layer position was remained, while it was altered when the thickness position was changed.
3. The reformation of previously destroyed texture and reactivation of slip systems were observed after multiple ARB cycles. Repetitive cutting and stacking in ARB result in cyclic changes of thickness position and then cyclic transition of texture and slip activities.
4. Shear deformation plays a critically important role in the distribution and fraction of shear textures, and also in the cyclic transition of texture and slip activities. When the shear deformation is relatively higher, less ARB cycles are needed for the reformation of shear texture.

Disclosure statement

No potential conflict of interest was reported by the authors

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