Deformation, recovery and recrystallization from heterogeneous shear bands in steel sheets

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Abstract. In order to clarify the mechanism of Goss texture formation along shear bands, the effect of cold rolling reduction on shear band formation and crystal orientation within shear bands and annealing texture were investigated in Fe-3%Si {111}<112> single crystals. Shear bands were formed intermittently during cold rolling; shear bands with smaller angles were formed earlier and those with larger angles were formed later. This result supports geometrical softening as a mechanism for shear band formation. Crystal rotation along shear bands became large in proportion to reduction. In calculation crystal rotation in ideal matrix, (111)[11-2], did not reach Goss, however, with consideration of orientation fluctuation the rotation angle exceeded Goss orientation and it coincided with the experimental data. After annealing recrystallized grains along shear bands were mainly Goss grains regardless of cold rolling reduction. The speculated reason for the dominance of Goss during annealing is that Goss cells have a comparatively lower density of dislocations and are surrounded by largely deformed areas.

1. Introduction

Properties of steel sheets, for instance deep drawing and magnetic flux density, largely depend on their textures and hence it is of great importance to control texture as desired. In the process, hot rolling, if necessary hot band annealing, cold rolling followed by final annealing are critical for controlling the texture of final products. In general, deformation structures after rolling are heterogeneous and recrystallization progresses heterogeneously through the process of nucleation and growth.

In poly-crystals which steel industries normally manufacture, vicinities of grain boundaries before deformation are one of the strongly preferable nucleation sites. Therefore grain sizes prior to cold rolling can be an essential parameter to determine texture after annealing following cold rolling [1]. Furthermore, in detail, boundaries which comprise {111} grains can be preferential nucleation sites because of local multiple slips [2].

For another preferential nucleation site, shear bands, which may occur after heavy planar strain in {111}<112> grains, are remarkably effective. Several studies about recrystallization texture after deformation of {111}<112> single crystals have argued that heterogeneous shear bands act as preferential nucleation sites of recrystallized grains with Goss orientation, {110}<001> [3-10]. However,
the mechanism of shear band formation and Goss texture development during annealing is not clearly understood although the Goss orientation is extremely important for steel sheets products.

Our final aim is to clarify the mechanism of Goss texture formation along shear bands. Studies about shear band formation and crystal orientation within them depending on cold rolling reduction have not been investigated so far though annealing texture are affected strongly by cold rolling reduction. Therefore, the purpose of study is to investigate the effect of cold rolling reduction on shear band formation, crystal orientation within shear bands and annealing texture in Fe-3%Si \{111\}<112> single crystals, which can help to achieve our final aim.

2. Experimental procedure

2.1 Sample preparation

An ingot of Fe-3%Si was produced in a vacuum melting furnace in the laboratory. After reheating it for 48 hours at 1573K in a nitrogen atmosphere, the ingot was cut into pieces to measure the crystal orientation using X-ray back-reflection Laue diffraction method. Then, specimens of \(111\)[11-2] orientation single crystal were cut into sizes of 20mm in width, 20-30mm in length and 2.85mm in thickness. The chemical composition of samples was Si 3.0, C 0.002, P 0.001, N 0.001wt% and Fe for the balance.

Regarding cold rolling, in order to deform the above small specimens effectively, a single crystal sample was inserted in a rectangular die in a polycrystalline hot band of 90mm width x 100mm length x 2.85mm thickness in size. Specimens were then sandwiched between two sheets of other hot bands of 90mm width x 100mm length x 2.0mm thickness in size, and the four sides of the three hot bands were welded together.

The sandwiched specimens were cold rolled by 28, 40, 50 and 68% reduction with multi-pass rolling as denoted in Table 1. In some specimens annealing for 10 seconds at 823K was performed to obtain recovered structures. As for annealing texture, samples were annealed for 30 minutes at 923K in a salt bath then quenched into water.

| Samples | Initial thickness(mm) | Reduction(%) | Final thickness(mm) |
|---------|-----------------------|--------------|---------------------|
| a       | 2.85                  | 28           | 2.05                |
| b       | 2.85                  | 40           | 1.71                |
| c       | 2.85                  | 50           | 1.43                |
| d       | 2.85                  | 68           | 0.92                |

2.2 Measurement and analysis of crystal orientations

In order to obtain microstructures mechanical polishing was performed in ND-RD (rolling and normal direction) sections followed by chemical etching with nitric acid and an ethanol solution. Orientation measurements and analyses were carried out in the ND-RD sections after chemical polished specimens using an EBSD (electron back-scattered diffraction pattern) system by TSL Solutions equipped in a SEM, JSM6500F(JEOL).

Quantitative data about crystal orientation within shear bands were taken from EBSD mapping data. In each specimen, three areas were taken and an area of a map was 30x40µm² in ND-RD sections with 0.1µm as the measuring step. The total points of the three maps in each specimen were, therefore, 417 thousand. Among these total points, less reliable values were eliminated; that is, if the CI values (confidence index values) in the analysis software in TSL Solutions were less than 0.1, the measurements points were eliminated. Furthermore, in the analysis of crystal orientation, rotation around TD (transverse direction) axis is important so that orientations within 10 degrees from the initial TD axis [-110] were analyzed and evaluated in this study.
2.3 Calculation of crystal rotation rates
In order to estimate crystal rotation within shear bands, Taylor factors and crystal orientation rates were calculated with a viscoplastic Taylor model [11]. Within shear bands simple shear was considered and, as for crystal rotation, crystal orientation rates were calculated as dividend by strains.

In relation to calculations considering orientation fluctuations, initial orientations were slightly changed around ND and RD axis of ideal matrix, (111)[11-2].

3. Results
3.1 Formation angles of shear bands
Optical micrographs of cold rolled specimens are shown in Fig.1. As the signature of each direction is very important because of single crystals, the orientations and signature of directions were corresponded in the schematic figure in the right side of Fig. 1. All specimens were observed in ND-RD sections and SBs (shear bands) were observed from lower left sides to upper right sides, which corresponded to previous studies [7,8,10]. And it was recognized that these SBs included the TD axis.

In the specimen with 28% reduction, only one type of SBs with the angle of 23 degrees (A1) to the RD (rolling direction) were formed as shown in Fig.1(a). In the 40% reduction in Fig. 1(b), two types of SBs were observed and this micrograph was very similar to the previous result by Ushioda and Hutchinson [8]. From Fig. 1(b) one type had a larger angle, 31 degrees (B1), and the other had a smaller angle, 15 degrees (B2). In the 50% reduction as shown in Fig. 1(c), several types of SBs could be observed and it was difficult to specify types of SBs, but the largest angles was 26 degrees (C1). In Fig. 1(c) black lines are deformation twins as denoted by arrows. In the 68% reduction in Fig. 1(d), it was the most difficult to specify SBs and the largest angles of SBs to RD were 30 degrees (D1).

3.2 Crystal rotation within shear bands
Crystal orientations within SBs were analyzed from EBSD data. In each specimen, the EBSD mapping data in the vicinity of the largest angle of SBs were taken into account. The important orientation fiber, which has a common TD axis, [-110], includes the initial orientation, (111)[11-2] and Goss, (110)[001], and, they have common Euler angle with 90degrees of $\phi_1$ and 45degrees $\phi_2$ (Bunge). Therefore, the orientation distribution was described as a function of $\Phi$, in which the initial (111)[11-2] is 55degrees and Goss 90degrees, as shown in Fig.2.

In Fig.2, orientation distribution from the initial became large in accordance with rolling reduction. The orientation end towards Goss (positive direction of $\Phi$) also became large. For example, the positive end in (a) 28% reduction did not reach Goss, however, those in (b),(c) and (d) with a larger reduction than 40% exceeded Goss to 120degrees of $\Phi$. It can be stated that the crystal rotation within SBs progressed in proportion to the cold rolling reduction.
Figure 1. Optical micrographs of cold rolled specimens in ND-RD sections; Cold rolling reductions are (a) 28%, (b) 40%, (c) 50% and (d) 68%. Arrows in (c) show deformation twins.

Figure 2. Orientation distribution around TD axis within 10 degrees. (a) A1 in 28%, (b) B1 in 40%, (c) C1 in 50% and (d) D1 in 68% of reduction.

3.3 Annealing texture
Fig.3 shows annealing microstructure and texture taken by EBSD. The microstructures are quality images of Kikuchi patterns [12]. Darker images indicate the area with higher density of dislocations. In 28% of reduction (Fig.3(a)), elongated recrystallized grains along SBs were observed and almost half of them were Goss grains. However, not all of SBs were occupied by recrystallized grains even after 30 minutes of annealing, and therefore, the annealing texture remained the initial orientation, (111)[11-2]. In 40% (Fig.3(b)), almost all SBs were occupied by recrystallized grains, and most of which were Goss grains. As the SBs did not cover all the area and the initial matrix still remained, the texture had two strong orientations, that is, the initial and Goss orientations.

In 50% (Fig.3(c)), recrystallization occurred in the whole area and previous SB regions before annealing could be observed as inclined areas with small grains. In this case the main texture was the Goss orientation. The situation of 68% (Fig.3(d)) was similar to that of 50%. Recrystallized grains with a homogenous size were observed in the whole area and the main texture was Goss orientation. On the
whole, it is recognized that recrystallized grains along SBs were mainly Goss regardless of cold rolling reduction.

Figure 3. Annealing microstructure described by Kikuchi pattern quality and \{100\} pole figures taken by EBSD. Annealing was performed for 30 minutes at 923K. Size of each area is 550\(\mu\)m x 800\(\mu\)m. The contour of pole figures is 4-8-12-16-20-24-28-32.

4. Discussion

4.1 Formation of shear bands

According to a previous study [8], two types of SBs were reported after 50% reduction; the one was 35degrees and the other 17degrees to RD in the ND-RD section. The situation is similar to the case of 40% reduction in the present study, in which two types of SBs were observed. However, this is not the general case, since only one type of SB after 28% reduction was observed, and the order of SB formation will be discussed below.

Fig.4 shows the transition of SB angles before and after rolling reduction. If SBs with a thickness of \(h_1\) are formed to \(h_2\) after reduction, the angle of \(\theta_1\) becomes \(\theta_2\). The angle \(\theta_2\) can be easily evaluated; \(\tan\theta_2 = \tan\theta_1 \times h_2^2/h_1^2\). According to this formula, the A1 with the angle of 23degrees in Fig.1(a)28% changes to 16.4degrees, which was very close to the B2 with the angle of 15 degrees in Fig.1(b)40%. The origin of B2, therefore, is speculated to be A1.

Similarly, B1 with the angle of 31degrees in Fig.1(b) changes to 22.6 degrees at a reduction of 50%. In Fig.1(c) several kinds of SBs were observed, and one of them had an angle close to 22.6 degrees (not denoted in Fig.1(c)), which was smaller than that of C1, 26 degrees. Therefore, the order of SB formation is considered to be the first A1 (=B2), then B1, and the last C1. From this discussion, if we have both a smaller and a larger angle of SBs at the same reduction, for example B2 and B1 in Fig.1(b), the former(B2) is considered to be formed earlier than the latter(B1). Furthermore, it can be mentioned that the first type of SBs is formed at a certain reduction, and then after some reduction, the second type of SBs is formed at one time, and this process can be continued during further reduction. Therefore, it is speculated that, the SB formation continues intermittently during deformation.
Concerning a mechanism for SB formation, geometrical softening has been suggested [13,14], in which crystal rotation and Taylor factors or M values were calculated considering simple shear within SBs dependent on shear strains and SB angle to RD, as shown in Fig. 5. This mechanism has been discussed also in other papers [7,8,13]. In one of the papers, however, a SB with a smaller angle (17 degrees) could not be explained by geometrical softening while that with larger angles (35 degrees) could be explained [8]. From the present discussion above, it is thought that the SBs with smaller angles were formed earlier and their initial angle just after formation should have been larger than 17 degrees. And, if the initial angle is larger than 19.5 degrees, geometrical softening can be one of the possible mechanisms for the SB formation because, in the angle from 19.5 to 45 degrees (the region of arrows in Fig. 5(b)), Taylor factors became smaller as deformation progressed in Fig. 5. Therefore, it can be mentioned that the present results support geometrical softening for the SB formation.

Figure 5. Crystal rotation and Taylor factors along shear bands considering simple shears. (a) The arrows denote the direction of the rotation, and (b) the region between arrows shows $dM/d\gamma<0$ (from 19.5 to 45 degrees).

4.2 Crystal rotation within shear bands after cold rolling

From Fig. 2, the orientation distribution within SBs introduced in higher rolling reduction became larger than that of SBs in a lower rolling reduction. First, crystal rotation within a SB was calculated with a consideration of simple shear in SBs. In this calculation, the angle of a SB was set to be 35 degrees to RD, since the initial angle of SBs was not clearly known and the maximum angle is 35 degrees among previous studies and this study, which is the study of Ushioda and Hutchinson [8].

Calculation results are shown in Fig. 6, in which rotation angles in a SB is dependent on strains of simple shear. Strains of simple shear are estimated easily if we have a straight maker before SB formation like deformation twins in Fig. 1(c). The estimated strain was 2.3 in this study and 2.9 in a previous study [8]. The rotation angle of a SB, however, was 15.5 degrees and did not reach the Goss orientation after strains of 2.3/2.9 or more.

The reason why calculated crystal rotation in a SB was 15.5 degrees is as follows; From Fig. 5 (a), if our starting point is 35 degrees, it rotates in the left direction. However the rotation stops at 19.5 degrees, since the crystal rotation rate is zero at that point. Subtraction of 19.5 from 35 is just 15.5. When geometrical slip system are considered, after rotation of 15.5 degrees one of {211} slip planes is parallel to the SB angle, and therefore, crystal rotation within the SB stops.

The calculation result above was not consistent with the experimental result as shown in Fig. 2. In order to consider the discrepancy, effects of orientation fluctuation just before SB formation were estimated. Even if the matrix \{111\}<112> is very stable in planar strains, after reduction more than 20%,
there can be some orientation fluctuations around RD and ND. Calculations of crystal rotation in SBs from initial orientations slightly different from ideal \{111\}<112> were performed. In these calculation results crystal rotation rate at 15.5 degrees in Fig. 5 (a) was not zero, and this means that crystal rotations within SBs continue in accordance with shear strains.

Results of rotation angle in SBs are shown in Fig. 7. With consideration of orientation fluctuations around ND axis, rotation angles increased with strains and it surpassed the Goss orientation in more than strains from 2 to 3, which are actual values of experiments. And from Fig. 7, if orientation fluctuation is larger, rotation angle progresses more largely, which means that, crystal rotations in SBs which formed at a later stage of rolling deformation can rotate in larger angles than those in SBs at an earlier stage of rolling.

**Figure 6.** Calculation result of rotation angles within a shear band with 35degrees of RD dependent on strains of simple shear. The arrows denote the matrix (0deg. ; (111)[11-2]) and Goss (35deg. ; (110)[001]).

**Figure 7.** Calculation result of rotation angles within a shear band with and without consideration of orientation fluctuation (OF). Numbers denotes fluctuation angles from initial matrix ((111)[11-2]) around normal direction.

**4.3 Formation of Goss texture during annealing**

From Fig.3 recrystallized grains along SBs were Goss orientation while orientation distributions within SBs after cold rolling were widely spread and Goss was not the special orientation. In order to obtain the information of dominance of Goss grains during annealing, recovered orientation maps along SBs were obtained with EBSD.

Euler angles \( \Phi \) of subgrains dependent on diameters are shown in Fig. 8. From this result, it is considered that Goss orientation becomes gradually dominant during subgrain growth while initial small subgrains do not have strong preferential orientations. Similar results were obtained by Furubayashi [6] and Tsuzaki et al. [10] though grain sizes in which Goss becomes dominant are different. In this study the width of SBs are from 2 to 5 micrometers and Goss becomes dominant during subgrain growth within SBs.

In the present study, recrystallized grains along SBs had mainly the Goss orientation and this result was similar to previous results along SBs [7,8,10] and along band structures [5,6,9]. The reason why Goss grains are dominant along SBs or band structures has been argued in these studies [5-10], however, any explanations that can describe the Goss formation well has not been obtained yet. Among the previous studies, Tuzaki et al. argued several hypotheses, and consequently, the most possible one is that Goss locates at the edge of the orientation distribution along SBs [10]. According to the hypothesis,
if Goss locates at the edge of the orientation distribution, Goss subgrains can recrystallize earlier than others because of high angle boundaries to the matrix. In Fig. 2, however, orientation distribution changed dependent on rolling reduction while the annealing orientations along SBs were almost Goss texture independent of reductions, and this result contradicted the hypothesis of “Goss location in the edge of the orientation distribution along SBs”.

Figure 8. Orientation distributions of subgrains within shear bands C1(reduction 50%) after annealing for 10s at 823K. Transverse direction is [10-1] within 10 degrees.

In order to consider another hypothesis for the dominance of Goss, careful observation has been done in EBSD maps. Figure 9 shows the orientation and quality maps in the vicinity of Goss along a SB in a sample of 40% reduction. The green color in Fig.9(a) denotes Goss orientation and white circles in Fig.9(b) show areas including Goss which are associated with Fig.9(a). From Fig.9 (b), the circled dark areas indicate comparatively large dislocation densities [12], but Goss areas (or Goss cells) inside circles are less dark than the surrounding areas. This means that, Goss cells exist in the region with larger amounts of dislocations, but the Goss themselves have smaller amounts of dislocations than just neighboring areas, presumably due to dynamic recovery. Therefore, it is speculated that Goss cells grow earlier than other cells and they consume surrounding areas with higher stored energies. However, the above reason, why Goss cells are formed as less deformed sites than other areas, has not been elucidated yet. The reason should be investigated further in terms of orientation stabilities of Goss grains during rolling and direct observation of dislocations around Goss cells.
Figure 9. The orientation and quality maps of EBSD. (a) The ND orientation and (b) the quality map of sample after 40% of reduction (white circles shows Goss orientations).

5. Summary
In order to clarify the mechanism of Goss texture formation along shear bands, the effect of cold rolling reduction on shear band formation and crystal orientation within shear bands and annealing texture were investigated in Fe-3%Si {111}<112> single crystals.

Shear bands were formed differently depending on rolling reduction; In 28% reduction, only one type of shear bands were observed, but in 40% two types and in more than 50% several types were formed. From estimation of the formation angle to the rolling direction, shear bands with smaller angles were formed earlier and those with larger angles were formed later. Thus, shear bands were formed intermittently during cold rolling. This result supports geometrical softening as a mechanism for shear band formation.

Crystal rotation along shear bands around TD//[1-10] progressed in accordance with rolling reduction; the orientation distribution from the initial matrix became large in proportion to the reduction and even exceeded Goss orientation when the rolling reduction became larger than 40%. Crystal rotation was calculated on the basis of simple shear deformation and in the initial matrix, (111)[11-2], rotation angle within shear bands did not reach the Goss orientation. With consideration of orientation fluctuation, however, the rotation angle progressed more and exceeded the Goss orientation. It means that crystal rotations in shear bands which formed at a later stage of deformation can rotate to larger angles than those in SBs at an earlier stage.

After annealing recrystallized grains along shear bands were mainly Goss grains regardless of cold rolling reduction. From analysis of recovered specimens Goss grains became dominant during subgrain growth within shear bands. The speculated reason for the dominance of Goss during annealing is that Goss cells have a comparatively lower density of dislocations and are surrounded by largely deformed areas. The reason why Goss cells are formed in less deformed than other areas along shear bands should be investigated further.

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