Role of Shear Bands in Annealing Texture Formation in 3\%Si–Fe (111)[11\overline{2}]

Single Crystals

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The nature of heterogeneous deformation bands and the mechanism of Goss texture formation have been studied in the process of cold rolling and annealing of 3\%Si–Fe (111)[11\overline{2}] single crystals. After cold rolling, two kinds of shear bands are observed. Wide shear bands (type I) make an angle of \(-35^\circ\) to the rolling direction in longitudinal section, whereas narrow shear bands (type II) have an angle of \(-17^\circ\). Rotations of crystallite orientations within the shear bands occur in the direction predicted by theory, however, the angles of the bands cannot be satisfactorily rationalised at present. The fine recrystallized grains nucleated along shear bands of type I have preferentially Goss orientation with a small dispersion (\(\pm 10^\circ\)) along TD/[110], whereas those nucleated within the type II bands have approximately twice as large an orientation spread. Following the nucleation along shear bands, recrystallization takes place by growth into the surrounding matrix.

KEY WORDS: cold rolling; annealing; shear band; recrystallization; texture; silicon steel; single crystal.

1. Introduction

It is well known that in the process of cold rolling and annealing, recrystallized grains are formed at specific nucleation sites such as initial grain boundary regions, deformation bands, deformation twins and preexisting precipitates, leading to preferential recrystallization textures.\(^1,2\) Therefore, heterogeneity in deformation structure becomes of great importance in order to control recrystallization texture.

This paper presents the role of heterogeneous deformation bands in recrystallization texture formation in 3\%Si–Fe (111)[11\overline{2}] single crystals. Many previous studies have been presented using single crystals with the same orientation, and have disclosed that heterogeneous deformation bands play a role as a preferential nucleation site of the recrystallized grains with Goss orientation ([110][001]). However, neither the nature of the heterogeneous deformation bands nor the mechanism of Goss texture formation has been elucidated.

In view of the above mentioned facts, the present study was aimed at obtaining more detailed information about heterogeneous deformation bands, which may help to elucidate the mechanism of Goss recrystallization texture formation.

2. Specimens and Experimental Procedure

Single crystals of 0.02\%C–3\%Si–Fe with (111)[11\overline{2}] as the initial orientation were processed as shown in Fig. 1. In the procedure (A), carbon was kept in solid solution prior to cold rolling by quenching the specimen from 1073 K into salt water. In this case, deformation twins were easily formed in the early stages of cold rolling, which were exploited to understand the nature of the heterogeneous deformation bands. In the procedure (B), the specimen was decarburized in 100 \% wet hydrogen atmosphere in order to avoid the formation of both second phases prior to cold rolling and deformation twins during cold rolling. Specimens cold rolled by 50 and 85 \% reduction were subjected to the following two different annealing processes:

1) annealing in salt bath (850°C–180 s) leading to complete recrystallization,
2) temperature gradient annealing which varies the structure from the cold rolled state to the recrystallized state within a single specimen.

Microstructural observation was carried out by SEM in the back scattered electron mode and TEM in addition to optical microscopy. Textures were investigated with both conventional X-ray diffraction method and electron channelling patterns.

3. Experimental Results

3.1. Formation of Heterogeneous Deformation Bands and Recrystallization along Deformation Bands

Microstructural variation of the specimen (procedure (B)) cold rolled 50 \% is shown in Fig. 2 as a function of annealing temperature using the temperature gradient annealing technique. Although the exact temperature is not known with this technique it must increase continuously along the specimens as, for example, from (a) to (d) in Fig. 2. As previously reported\(^3,5\) in the case of (111)[11\overline{2}] single crystals, cold rolling produces heterogeneous deformation bands, which play a role as preferential nucleation sites of recrystallized grains. The results shown in
Fig. 1. Experimental treatments showing the two different procedures (A) and (B) used in the present experiments.

Fig. 2. Optical micrograph showing different stages of recrystallization resulting from temperature gradient anneal (specimen from procedure (B) cold rolled 50%).

Fig. 2, however, have the following new features:

(1) Two types of deformation bands are recognized; wide bands with an angle of ~35° to the rolling direction (type I), narrow bands with an angle of ~17° to the rolling direction (type II) (Fig. 2(a)). In the transverse cross-section the bands form traces which are approximately parallel to the transverse direction of the sheet.

(2) The whole process of recrystallization could be followed in detail by making continuous examination along the gradient annealed specimens. It was clearly evident that recrystallization commences first (at the lowest temperature) along the type I bands so that these are completely consumed. At a somewhat later stage, recrystallization takes place along the type II bands while new grains in the type I bands begin to grow into the adjoining matrix. The latter stages of recrystallization are characterized principally by growth of the new shear band grains into the residual matrix. Nucleation of recrystallized grains within the matrix structure is relatively seldom observed. Thus, the shear band sites are completely dominant as regards the initiation of recrystallization in these samples. Examples of partly recrystallized structures are shown in Figs. 2(b) and 2(c).

(3) After complete recrystallization the original
type I bands are replaced by rows of fine grains, while growth of some of these into the surrounding matrix has produced regions of larger sized grains. To some extent, these larger grains are originated from grains nucleated in type II shear bands.

3.2. Orientations of Recrystallized Grains

Examples of preferential recrystallization along shear bands are presented in Fig. 3 by means of SEM micrographs in the back scattered electron mode. The specimen used was from procedure (B), cold rolled 50% and annealed in temperature gradient. Recrystallized grains from Nos. 1 to 24 are preferentially nucleated along a type I shear band, while grains from Nos. 30 to 48 are along shear band of type II. Some of these new grains, e.g. Nos. 1, 6 and 9, have already started to grow out into the adjacent matrix. Electron channelling contrast imaging also reveals recovered cell structure elongated on [110] slip planes in the matrix.

Crystal orientations of the grains mentioned above were determined by means of the electron channelling pattern technique (Fig. 4). Recrystallized grains preferentially nucleated along the type I shear band have Goss orientation, whose orientational dispersion along TD/[[110]] is only ±10°, whereas those nucleated along the type II shear band have larger dispersion (±25°) from Goss along TD/[[110]]

The electron channelling contrast images as well as (100) pole figures at the stage when recrystallization is complete are shown in Fig. 5 for a specimen from procedure (B), cold rolled 50% and annealed in temperature gradient. A region with fine grains in an oblique row is evidently the site where a type I shear band existed in the cold worked metal and has a well defined Goss texture similar to that observed at an earlier stage (Fig. 4(a)). Between these rows there are regions of larger grains which have nucleated and grown from type I and/or type II band into the deformed matrix structure. The texture of these larger grains seems to be comparable in sharpness to that developed in the type I bands but more perfect than that developed in the type II bands. These orientational data are quite limited but may indicate that some growth selection7,8 is taking place in addition to the dominant role of oriented nucleation. Specifically, the grains which grow most successfully into the matrix structure should be those nucleated in type I bands as well as those nuclei from the type II bands which are oriented closest to the Goss orientation.

3.3. Textures

Cold rolling and annealing textures (procedure (B)) are presented by [100] pole figures shown in Fig. 6. Since the (111)[112] orientation is one of the stable cold rolling textures, little fundamental change in texture is observed after cold rolling. Some orientational dispersion along TD/[[110]], however, is noted with increasing reduction from 50 to 85%.

Goss texture is the main annealing texture, together with a subcomponent of type (113)[332] which appears with increasing rolling reduction. These features of the textures are in good agreement with previous reports.3,4)

4. Discussion

4.1. Nature of the Heterogeneous Deformation Bands

In spite of the fact that the mechanisms of heterogeneous deformation bands have been discussed from various viewpoints previously3-6) the nature of the

![Fig. 4. (100) pole figure for grains nucleated along shear bands in Fig. 3. Recrystallized grains nucleated along a): shear band I, and b): shear band II.](image)

![Fig. 3. Back scattered electron image showing preferential recrystallization along shear bands (specimen from procedure (B) cold rolled 50%, annealed in temperature gradient).](image)
Fig. 5. Microstructure and selected grain orientations after completion of recrystallization for specimen from procedure (B) cold rolled 50 % and annealed in temperature gradient. 

Fig. 6. (200) pole figures of cold rolled and annealed sheets treated according to procedure (B).

depression bands themselves has not been fully elucidated. Therefore, this study places an emphasis on obtaining detailed experimental facts which are essential in discussing mechanisms.

In the case of the specimen with a large amount of carbon in solid solution prior to cold rolling, deformation twins are formed in the early passes of cold rolling (Fig. 7). These deformation twins are sharply sheared by the introduction of the deformation bands during the following reduction, which implies that these deformation bands are bands where shear strain is concentrated. Therefore, the more appropriate name is shear band instead of deformation band. The amount of shear strain concentrated in the shear band is equal to the displacement parallel to the band divided by the thickness of the band. A simple derivation leads to an expression for the shear strain \( \gamma \) as:

\[
\gamma = \frac{1}{\tan(\phi - \theta)} - \frac{1}{\tan \phi}
\]

where the angles, \( \phi \) and \( \theta \), are defined in Fig. 7.

As an example of the amount of shear strain, \( \gamma \) becomes 2.9 by inserting observed values \( \theta = 33^\circ \) and \( \phi = 50^\circ \) for the micrograph in Fig. 7 into Eq. (1). Since the total homogeneous strain of cold rolling the same specimen by 85 % corresponds to 1.9, the above value of \( \gamma \) can be regarded as an extremely large strain. This analysis allows us to conclude that shear bands may accommodate a large amount of the total imposed strain for the higher rolling reductions.

In previous studies\(^{17,18}\) heterogeneous deformation bands in \( \{111\}\{112\} \) single crystals were considered to stem from the local slip of \( \{211\}\{111\} \) slip system following uniform deformation on the \( \{110\}\{111\} \) slip system. In this case the deformation band is expected to make an angle of 20° to the rolling direction in the longitudinal section. Type II shear bands described in Sec. 3.1 have nearly the same angle and could, therefore, be a band of localized single slip. A problem with this interpretation is, however, that single slip gives rise to no lattice rotation which is difficult to rationalize with the deformation microstructure and recrystallization behaviour of the bands.
These features suggest that polyslip deformation should have been involved. It was impossible to assign a slip system that corresponds to type I shear bands with an angle of 35° to the rolling direction. Therefore, it is reasonable to conclude that the type I band is a kind of polyslip accommodation process activated to be compatible with the macroscopic shape change in specimen.

A model for shear band formation in brass having a duplex twinned structure with orientations [111]-
[112] has been presented by Yeung and Duggan. This model predicts a range of shear band angles between ~20 and ~35°. However, in view of the very different microstructures and slip systems as compared to the present case, any agreement would seem to be only fortuitous.

Calculations of crystallite rotation rates inside shear bands in (111)[112] oriented crystals together with the Taylor M factors which describe flow stress were presented previously. Unfortunately, a number of errors were made in that work so a corrected version is now presented in Fig. 8. For shear band angles around +35° there is a strong geometrical softening effect which could explain the tendency for strain localization (type I band). However, no such condition appears to exist in the vicinity of +17° where type II bands are observed. Furthermore, a tendency for geometrical softening would be expected around ~20° where no bands are observed experimentally. There is evidently a need for more detailed quantitative analysis in this regard.

4.2. Microstructure of Shear Bands

Fig. 9 shows a micrograph of shear bands observed by SEM in the back scattered electron mode for a specimen from procedure (A) cold rolled 85%. The following characteristics of shear banding were recognized:

(1) Deformation twins were sharply sheared by the introduction of shear bands.

(2) The microstructure of the shear band is too fine to be resolved.

(3) Primary [110] slip traces are recognizable in the matrix.

Thin foil observation by means of TEM (procedure (B) cold rolled 85%) shown in Fig. 10 manifests the above mentioned characteristics more clearly. The investigated plane is again the longitudinal section. The observed features are as follows:

(1) The shear band consists of elongated fine cells.

(2) Diffraction patterns obtained from the shear band show streaking corresponding to rotation of the lattice around the transverse direction, [110].

(3) The matrix is composed of elongated cells having boundaries parallel to the primary (110) slip plane.

These microscopical features support the nature of shear banding described in Sec. 4.1 in that primary (110) slip[11] is followed by the introduction of shear
bands in order to meet the demand of macroscopic shape change in the specimen. The sense of rotation of the crystallites inside the band (counter-clockwise in the figures presented here) is also in agreement with that for the calculations shown in Fig. 8.

4.3. Mechanism of Goss Texture Formation

At present no model can adequately explain why the Goss orientation is so strongly favoured for nucleation within the shear bands or, allowing for some spread in orientation, why bands of both types I and II recrystallize with a similar texture. The nuclei are, however, within the range of crystallite orientations observed in the deformation substructure of the shear bands (Fig. 10). An argument presented previously to that crystallites with Goss orientation exist at a region of sharpest lattice curvature within the shear band needs to be reconsidered in the light of the present findings. That explanation is still justifiable in the case of shear bands of type I, since the maximum rate of lattice rotation is predicted to occur when the crystallites within the band have rotated 35° from the original orientation, i.e., are at the Goss orientation. However, applying the same argument to type II shear band leads to the conclusion that the maximum rate of lattice rotation and, accordingly, the sharpest lattice curvature should occur after a rotation of only 17', corresponding to an orientation 18° removed from the Goss position (Fig. 8). A systematic deviation of 18° from Goss orientation is not observed for the grains nucleated in the type II shear bands although their orientations do spread more widely than those of the type I shear band nuclei (Fig. 4). The present experimental evidence does not, therefore, permit a general conclusion to be drawn regarding the mechanism for the origin of the Goss oriented nuclei within shear bands.

5. Conclusions

The main results are summarized as follows:

(1) Two kinds of shear band having high concentrations of shear strain are observed after rolling (111)[112] 3% Si-Fe single crystals.

(2) Wide shear bands (type I) make an angle of ~35° to the rolling direction in longitudinal section, whereas narrow shear bands (type II) have an angle of ~17°.

(3) Rotations of crystallite orientations within the shear bands occur in the direction predicted by theory, however, the angles of the bands cannot be satisfactorily rationalized at present.

(4) The fine recrystallized grains nucleated along shear bands of type I have preferentially Goss orientation with a small dispersion (±10°) along TD/[110], whereas those nucleated within the type II bands have approximately twice as large an orientation spread.

(5) Following the nucleation along shear bands, recrystallization takes place principally by growth of the shear band nuclei into the surrounding matrix.

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