Computer Color Mapping Analyses of Deformation Bands and Recrystallized Grains inside Elongated Grains near Surface of Hot-rolled Silicon Steel Sheet

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Computer color mapping of elongated grains near the surface of hot-rolled silicon steel sheet was performed with an image analyzer, using the data of crystallographic orientation and strain obtained from a Kossel pattern examination.

Matrix bands having two equivalent orientations of near (210) $\bar{1}23$ and (210) $1\bar{2}3$ elongated grains formed alternately near the surface of hot-rolled silicon steel sheet. The characteristic morphology comprised transverse deformation bands across a grain elongated in the rolling direction. The misorientation between the matrix bands separating the deformation bands was 40° (max.), whereas that inside each matrix band was $3\text{--}12^\circ$.

Most deformation bands are bordered by high angle grain boundaries with a width of 3 pixels, and are of complicated and highly curved form inside the elongated grain.

The elongated grains which were of near $\{111\}\langle 112 \rangle$ orientation had a large amount of strain and formed small recrystallized grains by strain induced boundary migration from the high energy area at the grain boundaries or from the deformation bands within the elongated grains.

The type and formation mechanism of the recrystallized grains can easily be observed by color mapping.

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I. Introduction

Improvements of magnetic properties of grain oriented silicon steel sheet have been closely coupled to improving the secondary recrystallization texture. It has remained unknown why Goss texture grains with an unstable (110) [001] orientation, which can grow in the cold rolled state, form preferentially in the secondary recrystallization process⁽¹⁾. To understand this phenomenon better, it is necessary to study in detail hot-rolled sheets, containing potential nuclei of the Goss grains, and the subsequent processes from hot rolling up to the secondary recrystallization. In grain oriented silicon steel, there is a distinct inhomogeneity of texture in the thickness direction of steel sheet formed during hot rolling, as well as microstructural inhomogeneity due to the localized $\alpha \rightarrow \alpha + \gamma$ transformation. The production of grain oriented silicon steel sheet has involved the skillful use of these inhomogeneities.

In order to clarify the formation of nuclei of secondary recrystallized grains and the mechanism of grain growth from nuclei to secondary recrystallized grains, it is necessary to extensively measure the orientation and strain of small areas ($5\text{--}20\ \mu\text{m}$) or small grains in the processes from hot rolling to the secondary recrystallization treatment. The Selected Area Channeling Pattern⁽²⁾ (SACP) and Kossel apparatus⁽³⁾ have recently been developed to accomplish this kind of work. In comparison with the previous etched-pit technique⁽⁴⁾ and micro Laue

method⁽⁵⁾, SACP technique shows a remarkable improvement in measurement accuracy ($\pm \pi/360$ rad) and analysis time (about 150 s/grain). Moreover, computer color mapping^{(6)–(9)} can be performed with an image analyser, using the orientation data measured by a Kossel pattern examination to clarify the mechanism by which secondary recrystallized grains with the Goss orientation preferentially develop.

This paper clarifies the structure of the elongated and recrystallized grains near the surface of hot-rolled silicon steel sheet. For this purpose, computer color mapping analyses of hot-rolled silicon steel sheet were performed with an image analyzer, using the orientation and strain data measured by a Kossel pattern examination.

II. Experimental Procedure

Hot-rolled sheets of grain oriented silicon steel with a 2.7 mm thickness were used. These sheets had the chemical composition (mass%) of Si: 3.35, Mn: 0.07, Se: 0.020, Sb: 0.025, and Mo: 0.013, and the hot-rolled sheets were characterized by a distinct microstructural inhomogeneity and multi-component texture⁽¹⁰⁾ through the thickness. Metallographic and textural examinations were made with an optical microscope and by the inverse pole figure method, respectively. In addition, (200) pole figures were also measured at 1/10 depth beneath the surface and in the central area of the hot-rolled silicon steel sheets.

Thin samples for the transmission Kossel (TK) pattern

examination were prepared by cutting hot-rolled sheets with a thickness of 2.7 mm into $30 \times 40 \text{ mm}^2$ pieces and mechanically grinding the upper side to a depth of 0.2 mm, and then grinding bottom side to a sheet thickness of 2.36 mm. The samples were chemically polished in a 3%HF + H₂O₂ solution to about 15 μm in thickness and finally etched with 3% nital. Representative areas of the microstructure were selected with an optical microscope, and the grain orientation and strain were assessed with a newly developed TK apparatus⁽¹¹⁾. Details of this TK examination and analysis method have been reported previously⁽³⁾⁽¹¹⁾. All of the TK patterns taken from elongated grains showed broadening of only the $\text{FeK}\alpha_1$ lines⁽¹²⁾⁽¹³⁾, because weak $\text{FeK}\alpha_2$ had disappeared due to a high level of strain in the material. The strain levels were analyzed by measuring the breadth of these broadened $\text{FeK}\alpha_1$ lines in the TK patterns. In contrast, all of the TK patterns taken from the recrystallized grains showed sharp lines of strong $\text{FeK}\alpha_1$ and weak $\text{FeK}\alpha_2$ as well as lines characteristic of a single crystal.

Computer color mapping was performed by an image analyzer (Luzex 5000)⁽¹⁴⁾⁽¹⁵⁾ using the orientation and strain data measured by the Kossel examination.

To do color mapping of the orientation of the elongated and recrystallized grains, the image analyzer was used on direct photographs from a color display. Orientation data from the Kossel pattern examination was converted by computational processing into the parameters⁽⁶⁾ necessary for stereographic presentation on a unit triangle showing the normal direction (ND) and rolling direction (RD). Three basic colors [blue (001), red (011), and green (111)] representing the orientations of the elongated and recrystallized grains were blended at 256 linear levels corresponding to the angle of deviation from each vertex. The linear interpolation method was used to map the orientation data from the measured areas in the elongated grains⁽¹⁶⁾⁽¹⁷⁾.

To map the strain, the width of the broadened Kossel lines due to the strain inside the elongated grains themselves was classified into three categories and photographed with cross-hatching⁽¹⁷⁾. Stronger cross-hatching shows the existence of a larger strain inside the elongated grains.

To map the character of the grain boundaries, the boundaries bordering individual elongated or recrystallized grains were classified into three categories by computational processing. The angles of ND and RD of adjoining grains were displayed with a width of 1 pixel representing an angle within 10°, 2 pixels, within 25°, and 3 pixels, more than 25°. Thus, a larger boundary width shows the higher angle among the adjoining elongated and recrystallized grains.

III. Experimental Results

Figure 1(A) shows the cross-sectional microstructure of the hot-rolled silicon steel sheet, which is inhomogeneous through the thickness of the sheet. Close to the surface, a mixed structure of elongated and recrystallized

Fig. 1 (A) optical micro-structure and (B) variation of X-ray inverse pole intensities (110), (200), (222) and (211) in the thickness direction of hot-rolled silicon steel sheet.

grains was formed, and a single structure of coarser grains elongated in the rolling direction was observed in the central area. Figure 1(B) shows the variation of (110), (200), (222) and (211) X-ray pole intensities in the thickness direction of the hot-rolled silicon steel sheet. The intensity of the (110) pole at 1/10 depth beneath the surface is exceedingly strong, whereas that of (200), (222) and (211) in the central area is strong in the order of (200), (222) and (211).

Figure 2 represents the (200) pole figures for (a) 1/10 depth beneath the surface and (b) in the central area of the hot-rolled silicon steel sheet. The dominant texture at 1/10 depth is $\{110\}\langle 001 \rangle$, whereas that in the central area is of a strong $\langle 110 \rangle$ fiber texture with orientations from $\{100\}\langle 011 \rangle$ via $\{112\}\langle 011 \rangle$ to $\{111\}\langle 011 \rangle$. From Figs. 1 and 2, it can be seen that the texture of hot-rolled silicon steel sheets varies greatly through the thickness of the sheet, the texture thus being exceedingly inhomogeneous.

Figures 3(a) and (b) are computer color maps showing the orientation and the strain of the elongated and

Fig. 2 Comparison of the (200) pole figures for (a) 1/10 depth beneath the steel surface and (b) in the central area of hot-rolled silicon steel sheet.

recrystallized grains at 1/10 depth beneath the surface of the hot-rolled silicon steel sheet, where (a) and (b) show the computer color maps of ND and RD, respectively. Figure 4 shows a color display of (a) a stereographic projection of the orientations of the elongated and recrystallized grains, (b) the strain in the elongated and recrystallized grains, and (c) the angle between the orientation of adjoining grains. Figure 5 shows a schematic diagram of the computer color map in Fig. 3.

The elongated grains (V), (U), and (T) in the upper half of the color micrographs in Figs. 3(a) and (b), and (J), (S), and (H) in the bottom half are elongated in the rolling direction, whereas only the elongated grain (K) in the central area is of the characteristic morphology having many deformation bands inside the elongated grain itself. Figure 6 shows the (200) pole figures obtained from the elongated grains in the color micrographs of Figs. 3(a) and (b).

As can be seen in Figs. 3 and 6, the elongated grain in the central area has two kinds of K_1 and K_2 matrix bands (regions with a common orientation⁽¹⁸⁾), which have formed alternately with two equivalent orientations of near (210) $[\bar{1}23]$ and (210) $[\bar{1}\bar{2}3]$, and have a comparatively large strain. The misorientation inside each matrix band of K_1 and K_2 is comparatively small at 3–12°, whereas that between the K_1 and K_2 matrix bands separating the deformation bands is exceedingly large at 40° (max.). It should be noted that most K_1 and K_2 deformation bands inside the elongated grain (K) have been displayed as high angle grain boundaries with a width of 3 pixels, or more than 25°, and have been formed with a complicated and highly curved boundary inside the elongated grain.

It is evident from Figs. 3 and 6 that the elongated grain (V) has a near $\{430\}\langle 001\rangle$ orientation, and elongated grains (U) and (T) have a $\{110\}\langle 114\rangle$ orientation rotated about 20° clockwise around the ND axis and near $\{111\}$

$\langle 112\rangle$ orientation, respectively. The elongated grain (T) has a large strain inside the crystal, and elongated grains (V) and (U) have comparatively small strains. It can also be seen that five recrystallized grains have formed in the elongated grain (T) with a near $\{111\}\langle 112\rangle$ orientation. From this color mapping, it is conceivable that the three recrystallized grains U' have formed by Strain Induced Boundary Migration (SIBM) from the elongated grain (U), and two recrystallized grains T' have formed from Deformation Bands (DB) inside the elongated grain (T).

Further, in Figs. 3 and 6, it is apparent that the elongated grains (J) and (S) have near $\{110\}-\{210\}\langle 001\rangle$ and $\{111\}\langle 112\rangle$ orientations, respectively, and that the elongated grain (H) has an orientation rotated 10° counter-clockwise from $\{110\}\langle 001\rangle$ around the ND axis. The elongated grain (S) has comparatively large strain, and the elongated grains (J) and (H) have small strains. From Figs. 3 and 6, five recrystallized grains have formed inside the elongated grain (S) with a near $\{111\}\langle 112\rangle$ orientation. It can be seen that the recrystallized grains J' and H' have formed by SIBM from the elongated grains (J) and (H), respectively, and that the recrystallized grain S' has formed from DB in the elongated grain (S).

IV. Discussion

In the elongated grains of (K) in the central area of Figs. 3 and 5, there are two kinds of matrix bands K_1 and K_2 having deformation bands nearly in the transverse direction within an elongated grain lying in the rolling direction. These matrix bands have formed alternately with two equivalent orientations of near (210) $[\bar{1}23]$ and (210) $[\bar{1}\bar{2}3]$, and with comparatively large strains. It should be noted that these deformation bands have been displayed as having high angle grain boundaries and manifest complicated and highly curved boundaries. It can also be seen that the grain boundaries lying between

Fig. 3 (a) Computer color mapping of the orientation of elongated grains parallel to the normal direction (ND) at 1/10 depth beneath the surface of hot-rolled silicon steel sheet. (b) Computer color mapping of the orientation of elongated grains parallel to the rolling direction (RD) at 1/10 depth beneath the surface of hot-rolled silicon steel sheet.

the elongated grains (K) and the top and bottom elongated grains show a distinctive curve; namely, the grain boundary between the elongated grains (K) and (J) is a virtually straight boundary nearly parallel to the rolling direction. In contrast, that between the elongated grains (K) and (T) or the elongated grains (K) and (U) is a complicated and highly curved boundary. It has already been reported that a similar structure to the elongated grain (K) occurred during the formation of a deformation band under the compressive deformation⁽¹⁸⁾ of pure iron. In a comparison of hot-rolled silicon steel sheet and pure

iron, it should be noted that the formation of these deformation bands occurs at elevated temperatures during hot rolling, and in the vicinity of the steel surface, where the energy is the highest. Also, in calculating the pencil glide in BCC metals, Dillamore and Katoh⁽¹⁹⁾ have pointed out that the crystallographic orientations from the (110) plane to (411) were unstable, and that these orientations changed to final stable or orientations of (100) and (111). Although it is considered that the elongated grain (K) having deformation bands has been shifted to a lower energy levels during hot rolling and therefore manifests the char-

Fig. 4 Color display of (A) a stereographic projection of three basic colors, blue (001), red (011), and green (111), (B) strain of elongated grains, and (C) boundary width showing angle of the orientation of adjoining grains.

Fig. 5 Schematic diagram of the elongated grains and recrystallized grains shown in Fig. 3.

acteristic morphology seen in the color photographs in Fig. 3, it can be pointed out that the formation of an exceedingly large misorientation of 40° (max.) between the K_1 and K_2 matrix bands is stable in terms of energy and, in this case, that no recrystallization has taken place. This suggests that the region near the surface of hot-rolled silicon steel sheet is unstable at the highest energy level from a crystallographic aspect and that the nuclei for secondary recrystallized grains were generated in this region.

As another point requiring emphasis, the computer

color mapping⁽²⁰⁾ of the primary recrystallized grains near the growing front of secondary recrystallized Goss grains showed that the alternate configuration of primary recrystallized grains having the $\{342\}\langle 430 \rangle$ orientation was virtually unconsumed by secondary recrystallized Goss grains, which is beneficial for decreasing the boundary energy during secondary recrystallization annealing.

It should be noted that the elongated grains (T) and (S) with near $\{111\}\langle 112 \rangle$ orientation seen in the upper and lower halves of the color micrographs in Fig. 3, these elongated grains have larger strains than the others, bordering the highly curved boundaries. Large amounts of strain accumulated in these elongated grains due to the formation of the complicated dislocation networks of small cells during hot rolling. Therefore, the formation of recrystallized grains took place from DB of this matrix or by SIBM from high-energy areas in the boundary. In this study, the types and mechanism of formation of these recrystallized grains can be identified quite easily by color mapping.

Figure 7 is a simplified diagram showing typical examples of the elongated grains in Fig. 3. No recrystallized grains formed from K_1 and K_2 matrix bands inside the elongated grains, due to the lower energy existing after the alternate formation of matrix bands with deformation bands during hot rolling; thus, the type of grain formation is quite different from that responsible for elongated grains such as those of the near $\{111\}\langle 112 \rangle$

Fig. 6 (200) pole figures showing the crystallographic orientations of the elongated grains and recrystallized grains in Fig. 3.

(1) No recrystallized grain

(Pairs of two equivalent matrix bands of near $\{210\}\langle 123 \rangle$ orientation)

Fig. 8 Stereographic diagrams of preferential occurrence of crystallographic planes of elongated grains between (a) near-surface and (b) central area of hot-rolled silicon steel sheets.

(2) Small recrystallized grains

(Local large strain of elongated grains of near $\{111\}\langle 112 \rangle$ orientation)

Fig. 7 Schematic drawings showing typical examples of elongated grains.

orientation, in which small recrystallized grains formed preferentially from local area with a large strain.

Finally, to discuss the difference in the textural formation associated with elongated grains at the near-surface and central area in hot-rolled silicon steel sheets. Figure 8 shows a comparison of the frequencies of occurrence of specific crystallographic planes associated with elongated grains in these two areas. In the central area (b), elongated grains formed preferentially⁽²¹⁾ with final stable orientations of (100) and (111) and with moderate strains inside the elongated grains themselves. Conversely, in the near-

surface area (a), elongated grains with (111)~(110) planes were formed preferentially, and those with the (100) plane were rarely seen. In addition, grains with a near (210) plane formed, as shown in the cross-hatched area of Fig. 8(a). Here, it should be emphasized that the matrix bands with two equivalent orientations and large misorientations were formed due to the formation of deformation bands inside the (210) elongated grains. This phenomenon, which extended the stereographic orientation area associated with the frequency of occurrences of specific planes, takes place due to the preferential formation of deformation bands inside elongated grains, because extra energy such as shear stress is added at the near-surface rather than at the central area during hot-rolling. However, no new grains formed from these deformation bands at the near-surface. It is considered that this experimental result may prove the production at the near-surface of smaller strain than inside elongated grains of the $\{111\}\langle 112 \rangle$ orientation or some reduction of the total energy by the formation of two equivalent matrix bands inside the elongated grains.

V. Conclusion

To clarify the formation behavior of deformation

bands and recrystallized grains inside the elongated grains near the surface of hot-rolled silicon steel sheet, computer color mapping was performed with an image analyzer, using the data of crystallographic orientation and strain measured by a Kossel pattern examination. The experimental results are summarized as follows.

(1) Matrix bands having two equivalent orientations of near (210) $[\bar{1}23]$ and (210) $[\bar{1}\bar{2}3]$ inside an elongated grain formed alternately near the surface of the hot-rolled silicon steel sheet with a characteristic morphology of deformation bands forming in the nearly transverse direction in an elongated grain lying in the rolling direction. The misorientation between the matrix bands separating the deformation bands was 40° (max.), whereas that inside each matrix band was only $3\text{--}12^\circ$.

(2) Most of deformation bands were bordered by high angle grain boundaries with the boundary width of 3 pixels, and formed with complicated and highly curved boundaries inside the elongated grain.

(3) The elongated grains of nearly $\{111\}\langle 112\rangle$ orientation had large strain, and formed small recrystallized grains by stress induced boundary migration from the high energy area in the boundaries or from deformation bands inside the elongated grains themselves.

(4) The type and mechanism of formation of these recrystallized grains can be identified easily by color mapping.

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