Evolution of Goss Orientation during Rapid Heating for Primary Recrystallization in Grain-oriented Electrical Steel

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To obtain ideal Goss-oriented Fe-3.1%Si electrical steel, we studied the Goss orientation and microstructure during the various processes from hot-band annealing to the primary recrystallization. In particular, we examined the effect of the heating rate (20°C/s and 150°C/s) on the primary recrystallization behavior. In the annealed hot-band, the surface and middle layers have different textures. In the surface layer, a weak Goss texture developed, while in the inner layer, very strong α-fiber and weak γ-fiber texture were formed. The cold-rolled sheet had a relatively strong α-fiber and weak γ-fiber texture. In the cold-rolled sheet, the Goss oriented grains with an average size of 0.15 μm were more in the surface layer than in the middle layer. One part of the Goss-oriented grains originated from the annealed hot-band, while the other was formed during the cold rolling. During recrystallization, the size of the Goss-oriented grains was not influenced by the heating rate. However, the fraction and distribution of the grains depended on the heating rate. For high heating rates, the fraction of Goss grains is larger, and these grains had similar distributions in both the surface and middle layers.

KEY WORDS: grain-oriented electrical steel; Goss orientation; primary recrystallization; rapid heating process; X-ray texture; OIM (orientation image mapping).

1. Introduction

Magnetic properties are important for the grain-oriented electrical steel used as the core material of transformers. Studies have been carried out to reduce the core loss and increase the magnetic flux density and permeability by controlling the microstructure and texture via the addition of alloying elements as well as through process control and heat treatment. To improve the properties of grain-oriented electrical steel, it is important to use textures that have the <100> direction that eases magnetization. Textures that have this direction include the {100}<001> Cube texture in which the rolling direction and the direction normal to the rolling plane are the <100> direction, and the {110}<001> Goss texture in which the rolling direction is the <100> direction but the direction normal to the rolling plane is the <110> direction. The orientation that is currently technically feasible is the {110}<001> Goss orientation. Thus, it is essential for grain-oriented electrical steel to have a Goss orientation with a fairly high degree of integration. Generally, this is achieved using advanced texture-control technology involving the addition of alloying elements as well as processing and heat treatment. Studies on controlling processes such as hot rolling, hot-band annealing, cold rolling, primary recrystallization, and secondary recrystallization, as well as on manufacturing electrical steels with a highly developed Goss texture have been conducted.

This study aims to contribute to the manufacture of grain-oriented electrical steels with an ideal Goss texture by examining changes in the Goss orientation and microstructure during the development of the texture in various processes from the annealed hot-rolled plate to the primary recrystallization. We believed that if a microstructure with many Goss-oriented grains was produced after the primary recrystallization, a Goss texture with a degree of integration close to the ideal degree of integration could be obtained after the secondary recrystallization. We therefore chose to accelerate the heating rate during the primary recrystallization after cold rolling.

In each process, we analyzed the microstructure and the crystal orientation using X-ray texture analysis and electron back-scattered diffraction (EBSD) in SEM. We used EBSD to investigate the shape of the grains and the size and distribution of Goss-oriented grains.

2. Experimental Procedure

The material used in this investigation was vacuum-melted Fe-3.1%Si grain-oriented electrical steel with the chemical composition 0.06% C, 0.1% Mn, and 0.02% P. The start sheet was an annealed hot-band with a thickness of 2.0 mm, which was cold rolled to 0.30 mm in thickness. To study the effect of the heating rate on the primary recrystallization behavior, cold-rolled samples were heated at a rate of 20°C/s (normal speed) and 150°C/s (rapid heating) to almost 700°C. Samples were extracted at different holding times and estimated fractions of recrystallization. The microstructure, including the grain size, distribution, frac-
tion of Goss-oriented grains, and texture, was studied with optical microscopy, X-ray pole figures, and OIM (orientation image mapping) based on EBSD.

2.1. X-ray Texture Analysis
Considering that the texture may not be consistent throughout the sheet, it was measured at several points: the surface layer of the specimen (s = 0.95), the 1/8-layer (s = 0.75), the 1/4-layer (s = 0.50), and the 1/2-layer (s = 0.0, middle layer). The surface of the specimen was polished carefully to avoid a deformed structure due to layer separation, and it was then etched.

The pole figure was measured at an accelerating voltage of 40 kV and a current of 30 mA using an X-ray diffractometer (Bruker-AXS D-5005 model) with Co-target (wavelength: 0.17902 nm) for {110}, {200}, and {211}. The complete orientation distribution function (ODF) was calculated using the harmonic method and a positivity condition.8,9) The pole figure was measured at 0–70° specimen inclination at intervals of 5° and 0–360° specimen rotation at intervals of 5° using the Schulz reflection method.

2.2. EBSD Analysis
To check the grain shape and orientation of the annealed hot-band, the microstructure of the cold-rolled sheet, and the partially recrystallized phenomena on sheets with heat treatment, we used an FE-SEM (Hitachi S-4300SE, JEOL 6500F) with electron back-scattered diffraction. OIM software (TSL, INCA) was used to index the pattern and to evaluate the orientation data. The step sizes were 2.4 μm, 0.5 μm, and 0.06 μm and the total measured area was 0.6 mm × 2.3 mm, 100 μm × 252 μm, or 9 μm × 26 μm depending on the step size. A color key was used to show the crystal orientation, and if necessary different colors were used to illustrate different components of the texture.

3. Results and Discussion
Figure 1 shows the result of OIM using EBSD on an annealed hot-band and ODF (ϕ = 45° section) for the surface and middle layers. The texture is different for the surface and middle layers. Weak {110}<001> Goss orientation is found in the surface layer. Goss orientation occurs when shear deformation occurs in a metal with a BCC crystal structure,10) and this result shows that shear deformation occurs on the surface during the hot-rolling process. The middle layer (s = 0.0) of the sheet has a totally different texture. Strong α-fiber texture (<110> RD texture) is formed with a strong {100}<011> rotated Cube component and a weak γ-fiber texture (<111> ND texture). Such a texture occurs when plane-strain deformation conditions are satisfied during rolling in a BCC metal.10) Therefore, a Goss component exists on the surface of the annealed hot-band as a result of shear deformation but not in the inner layer. It may be possible to form Goss components even inside the sheet if the hot-rolling conditions are controlled in such a way that shear deformation affects the inside.

Figure 2 shows the optical microstructure of the grain-oriented electrical steel after cold rolling in the RD (rolling direction)-ND (normal direction) section. Elongated grains parallel to the rolling direction and shear bands are formed during the cold rolling. Figure 3 indicates the texture of the layers of the cold-rolled sheet. To clearly illustrate the cold-rolled texture, a ϕ = 45° section of the ODF is presented. Strong α-fiber texture and weak γ-fiber texture are developed in every layer. The maximum orientation density becomes stronger closer to the surface, and the {111}<110> component is more strongly developed than the {111}<112> component in the γ-fiber texture. This type of texture can be shown by simulation of the rolling texture using the Taylor model.11,12) For a microstructure with elongated grains of annealed hot-band, the plane-strain deformation condition is satisfied by the relaxed constrained model (RC-SC model).10)

Figure 4 shows an orientation image mapping of the cold-rolled sheet obtained by EBSD with a step size of 0.06 μm near the surface (s = 0.95, 0.75) and in the middle layer (s = 0.0). Red indicates the {110}<001> Goss orientation.
(Euler angle $\{\phi_1, \Phi, \phi_2\} = \{90^\circ, 90^\circ, 45^\circ\}$) and blue the $\{100\}<001>$ Cube orientation ($\{0^\circ, 0^\circ, 0^\circ\}$). The orientations $\{45^\circ, 0^\circ, 45^\circ\}$, $\{0^\circ, 30^\circ, 45^\circ\}$, $\{0^\circ, 45^\circ, 45^\circ\}$, $\{0^\circ, 60^\circ, 45^\circ\}$, $\{0^\circ, 75^\circ, 45^\circ\}$, and $\{0^\circ, 90^\circ, 45^\circ\}$ indicate $\alpha$-fiber texture and the orientations $\{60^\circ, 54.7^\circ, 45^\circ\}$, $\{75^\circ, 54.7^\circ, 45^\circ\}$, and $\{90^\circ, 54.7^\circ, 45^\circ\}$ indicate $\gamma$-fiber texture. The tolerance angle was 15° for the given orientation. Every layer has wide grains of 2–10 $\mu$m in breadth and also grains that are elongated in the rolling direction and have a width of less than 1 $\mu$m. The wide grains mostly have $\alpha$-fiber orientation. The narrow and elongated grains mostly have $\gamma$-fiber orientation; a micro band is developed parallel to the rolling direction and a shear band is inclined at 20–40° from the rolling direction. The black area indicates points that were not indexed during the OIM scan. The Goss-oriented grains, which will be able to operate as a seed for the secondary recrystallization, are mostly formed as small grains in strongly deformed micro or shear bands and are especially found in consecutive shear bands on the surface layer. The fraction of Goss-oriented grains is 0.6% at the $s = 0.95$ (surface) layer, 0.23% at the $s = 0.75$ layer, and 0.13% at the $s = 0.0$ (middle) layer. Thus, a larger number of the Goss-oriented grains are present near the surface. This seems to be because the Goss orientation in the annealed hot-band before cold rolling has developed near the surface. In addition, in order for the $\{100\}<011>$ or $\{111\}<011>$ orientation developed in the middle zone of the annealed hot-band to have Goss orientation during the cold rolling, at least 62.8° or 46° should be rotated. This is more difficult than rotating toward Goss orientation from the orientation near Goss orientation existing on the surface layer, so that Goss orientation exists more in the surface layer than the middle layer. Moreover, a rotation of 35.3° for the $\{111\}<112>$ orientation of the $\gamma$-fiber to Goss orientation is profitable. However, this increases the fraction with Goss orientation only slightly because the middle layer of the annealed hot-band has low $\{111\}<112>$ orientation density.

The Goss grains in the cold-rolled sheet are small (average grain size of 0.15 $\mu$m). The image quality (IQ) parameter was examined to check whether the Goss grains are formed by cold rolling or come from Goss-oriented grains on the annealed hot-band. The IQ describes the quality of an electron back-scattered diffraction pattern. Any distortions to the crystal lattice within the diffracting volume will produce lower-quality diffraction patterns. This enables the IQ parameter to provide a qualitative description of the strain distribution in a microstructure. Figure 5 expands the

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Fig. 3. Texture across thickness ($\phi_2 = 45^\circ$ section) of cold-rolled grain-oriented electrical steel.

Fig. 4. Orientation mapping of cold-rolled sheet obtained by EBSD with step size of 0.06 $\mu$m near surface ($s = 0.95, 0.75$) and in middle layer ($s = 0.0$), ND-RD section. Colors indicate orientations as in legend.

Fig. 5. EBSD image quality (IQ) map combined with corresponding crystal orientation of cold-rolled sheet obtained with step size of 0.06 $\mu$m at surface ($s = 0.95$). Colors indicate orientations and grayscale for EBSD IQ. Darker gray shades in image indicate lower IQ values. Goss-oriented grains (red) at A and B have high IQ values and those at C and D have low IQ values.
bottom of the s = 0.95 layer (in Fig. 4), shows the EBSD image quality in grayscale, and overlaps the colors indicating the crystal orientation. Red indicates both bright (A, B, high image quality) and dark (C, D, low image quality) parts of grains with Goss orientation. This means that the area with lower IQ (grains C, D) was deformed during cold-rolling. If the Goss-oriented grain is detected in such deformed area, this Goss-oriented grain should be generated newly during cold rolling. The degree of deformation could not determine quantitatively yet with the IQ value. This should be research in future. This shows that both original Goss grains (grains A, B) and newly formed Goss grains from the cold rolling (grains C, D) exist. This result is similar to that of a previous study in which a single crystal with Goss orientation was rolled. Therefore, to achieve more grains with Goss orientation in a cold-rolled sheet, the sheet should be strongly deformed to create more micro or shear bands. In addition, many Goss grains should exist, and γ-fiber texture with a strong {111}<112> component may be preferable to α-fiber.

Several stages in the recrystallization process with heating rates of 150°C/s and 20°C/s are shown in Figs. 6 and 7 (optical microstructure) and Figs. 8 and 9 (OIM). The small new grains form and grow mostly in the severely deformed micro or shear band at an early stage of recrystallization. The fraction of recrystallization is estimated from the optical microstructure and OIM obtained by EBSD with a step size of 0.5 μm in whole thickness. The heating rate for the recrystallization did not significantly influence the microstructure. The average size of the recrystallized grains after rapid heating is similar to that after slow heating. The broad elongated grains remain to a late stage of the recrystallization process in both cases. This indicates that these grains have low stored energy after the cold rolling. The average grain size and the fraction of Goss-oriented grain is shown in Figs. 10 and 11. The size of the Goss-oriented grains was about 1 μm at the beginning of the recrystallization, but it finally reached about 2.5 μm. The size of the Goss grains according to the fraction of recrystallization was not influenced by the heating rate. However, the fraction and distribution of the Goss grains did depend on the heating rate. After 97% recrystallization, the fraction of Goss-oriented grains was 2.15% with rapid heating and 1.73% with normal heating. After recrystallization at the normal heating rate, the surface layer shows a higher fraction of Goss grains than the middle layer, as shown in the cold-rolled sheet. With
rapid heating, the surface and middle layers have a similar
distribution of Goss grains. This indicates that rapid heating
promotes the creation of Goss grains inside the sheet too.
This seems to be because the stored energy archived during
the cold rolling remains to a late stage in the recrystalliza-
tion during rapid heating, and therefore there are more
opportunities to form Goss grains.

Figures 12 and 13 show the X-ray texture of the surface
and middle layers according to the recrystallization fraction
when a cold-rolled sheet is heated at 150°C/s and 20°C/s. In
both cases, the texture is more strongly developed on the
surface than inside. There is no change in the texture at the
beginning of the recrystallization, but as the recrystallization
reaches 30% or more, the γ-fiber texture changes earlier than
the strongly developed α-fiber. The {111}⟨110⟩ component
is more strongly developed than the {111}⟨112⟩ component
in the γ-fiber texture; this component has lower strength.
With the recrystallization, the intensity of the α-fiber is
reduced. The {111}⟨110⟩ component is almost consumed
and the \{111\}<112> component moves slightly toward the \{554\}<225> component (Euler angle = \{90°, 60°, 45°\}). Also, in specimens with more than 69% recrystallization, the \{411\}<148> orientation existing in \{20°, 20°, 45°\} is formed weakly. In the recrystallization process, increasing \{554\}<225> and \{411\}<148> orientations are related to the \(\Sigma 19\), \(\Sigma 9\) CSL relationship to the Goss orientation respectively. These are known to be important for the growth of Goss orientation during secondary recrystallization.\(^{16,17}\)

Changes depending on the heating rate are seen in the \(\alpha\)-fiber texture. For rapid heating, the \(\alpha\)-fiber texture exists until 97% recrystallization, but for slow heating, the \(\alpha\)-fiber texture almost disappears. This indicates that time is necessary for \(\alpha\)-fiber recrystallization. Thus, grains with \(\gamma\)-fiber texture are more deformed during cold rolling than those with \(\alpha\)-fiber texture, as discussed above (see also Fig. 4). These changes in the texture during the primary recrystallization can be confirmed using the orientation density. \textbf{Figures 14} and \textbf{15} show the orientation density changes according to the recrystallization fraction of some important orientation components; they are shown before and after recrystallization in overall layers of the sheet. The intensity of the Goss components is the sum of the intensity of 10 degrees around the exact Goss orientation. \textbf{Figures 12} and \textbf{13} show the texture of rapid-heated (150°C/s) and normal-heated (20°C/s) sheets extracted at different fractions of recrystallization.\(^{16,17}\)
the γ-fiber texture decreases first. The \{100\}<011> component included in the α-fiber texture exists almost up to the end of the recrystallization when the heating rate is high. During recrystallization, another component with significant changes is <100>RD fiber (γ-fiber) and its density rapidly increases. The intensity of the Goss components important for the secondary recrystallization increases slowly as the recrystallization progresses. The Goss intensity increases with the heating rate, as shown in the OIM result.

4. Conclusions

We analyzed changes in the texture and microstructure at heating rates of 150°C/s and 20°C/s for the primary recrystallization after the cold rolling of an annealed hot-band. We used OIM analysis based on EBSD and X-ray texture to examine the behavior of the Goss-oriented grains. The findings are as follows:

(1) In the annealed hot-band, the surface and middle layers had different textures. In the surface layer, a weak Goss texture developed, whereas in the inner layer, strong α-fiber and weak γ-fiber textures were formed.

(2) The cold-rolled sheet showed relatively strong α-fiber and weak γ-fiber textures in all layers. In the cold-rolled sheet, the number of Goss grains with an average size of 0.15 μm was more in the surface layer than in the middle layer. They were mostly formed in strongly deformed micro or shear bands. One part of the Goss-oriented grains originated from the annealed hot-band, while the other was formed during the cold rolling.

(3) During recrystallization, the size of the Goss-oriented grains was not influenced by the heating rate. However, the fraction and distribution of these grains depended on the heating rate. For high heating rates, the fraction of Goss grains is larger, and these grains had similar distributions in both the surface and middle layers.

REFERENCES

1) Y. Yoshitomi, K. Iwayama, K. Kuroki, Y. Matuo and H. Masui: J. Japan Inst. Metals, 57 (1993), 612.
2) M. Matsuo, T. Sakai, M. Tanino, T. Shindo and S. Hayami: Proc. 6th Int. Conf. on Textures of Materials, ed. by S. Nagashima, ISIJ, Tokyo, (1981), 918.
3) K. Iwayama and T. Haratani: J. Magn. Magn. Mater., 19 (1980), 15.
4) A. Datta: IEEE Trans. on Mag., MAG-12 (1976), No. 6, 867.
5) M. F. Littmann: Metall. Trans. A, 6A (1975), 1041.
6) Z. Xia, Y. Kang and Q. Wang: J. Magn. Magn. Mater., 320 (2008), 3229.
7) N. P. Goss: US Patent (1934), No. 1, 965, 559.
8) H. J. Bunge: Texture Analysis in Materials Science, Butterworths Pub., London, (1982), 47.
9) M. Dahms and H. J. Bunge: J. Appl. Cryst., 22 (1989) 439.
10) N. J. Park, M. K. Lee and M. Y. Huh: J. Kor. Inst. Met. & Mater., 38 (2000), 599.
11) G. I. Taylor: J. Inst. Met., 62 (1938), 307.
12) J. F. Bishop and R. Hill: Philos. Mag., Ser. 7, 42 (1951), 414, 1298.
13) S. T. Wardle, L. S. Lin, A. Cetel and B. L. Adams: Proc. 52nd Annual Meeting of the Microscopy Society of America, MSA, Reston, VA, (1994), 680.
14) D. Dorner, S. Zaefferer and D. Raabe: Acta Mater., 55 (2007), 2519.
15) S. H. Choi and Y. S. Jin: Mater. Sci. Eng., A 371 (2004), 149.
16) R. Shinmizu and J. Harase: Acta Metall., 37 (1989), 1241.
17) H. Homma and B. Hutchinson: Acta Mater., 51 (2003), 3795.