{001}<210> Texture Development by Two-stage Cold Rolling Method in Non-oriented Electrical Steel

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The {001}<210> texture, which is preferable for good magnetic properties in non-oriented electrical steel, is enhanced by the two-stage cold rolling method in which the intermediate annealing temperature is 640°C. The mechanism of {001}<210> texture development by two-stage cold rolling method was investigated by the measurement of microtexture changes during annealing with EBSP (Electron Back Scattering Pattern). The intermediately annealed sheet, whose recrystallized fraction is 60%, mainly consists of <111>//ND small equiaxed recrystallized grains and <110>//RD elongated deformed grains. During final annealing, the growth of <111>//ND recrystallized grains is suppressed and {001}<210> grains grow consuming <111>//ND recrystallized grains. This could be caused by the strain introduced by second cold rolling in <111>//ND recrystallized grains. Consequently, {001}<210> grains dominate the overall texture of the final annealed sheet.

KEY WORDS: electrical steel; metallography; magnetic property; texture; recrystallization.

1. Introduction

Electrical steel sheets are used as core laminations for motors and transformers. In order to reduce the energy loss of these electrical devices, it is necessary to improve the magnetic properties of their core material. It is well known that magnetization is easiest in the <100> direction of iron crystals, and the crystalline texture of the core material therefore has a large effect on magnetic properties.

The non-oriented electrical steel sheets used in small- and medium-size motors are generally punched in ring cores and laminated. Therefore, they should show low iron loss and high magnetic induction in the circumferential direction. The <100>//ND crystalline texture is most favorable to circumferential magnetic properties.¹⁾ However, non-oriented electrical steel sheets are manufactured by a one-stage or two-stage cold rolling method, and <111>//ND grains recrystallize preferentially as a result of annealing.

Heyer *et al.* investigated the effect of cold rolling reduction on recrystallization texture in the one-stage cold rolling method, and showed that heavy cold-rolling reduction on the order of 97.5% caused the development of the {001}<210> texture,²⁾ but this degree of reduction is not practical for the manufacture of steel sheets in industrial processes.

Shimazu *et al.* investigated the effect of the intermediate annealing temperature on the final-annealed sheet texture in the two-stage cold rolling method by varying the intermediate annealing temperature between

700 and 900°C, and reported that intermediate annealing at 700°C produced a near {011}<100> texture after final annealing.³⁾ This investigation also showed that recrystallization in intermediately annealed sheets was 100% complete, as in the conventional two-stage cold rolling manufacturing process for electrical steel.

Nakamura *et al.* reported that the {001}<210> texture was enhanced by a two-stage cold rolling method in which the intermediately annealed sheet partially recrystallized.⁴⁾ Their method seems to be suitable for industrial production of non-oriented electrical steel sheet with the <001>//ND texture and high magnetic induction.

In the present study, the formation mechanism of the {001}<210> texture in the two-stage cold rolling method was investigated. It is well known that recrystallized grains originate at heterogeneities in deformed grains. Therefore, the microtexture, which means the morphological aspects of the microstructure with a knowledge of the local crystalline orientation in the μm range, is most important for understanding the formation of the recrystallization texture. However, the classical methods of investigating texture, such as X-ray diffraction pole figures, yield no information about the microtexture. In this study, electron back scattering pattern (EBSP) analysis^{5–7)} was used to evaluate the microtexture and its changes during annealing. Two-dimensional crystalline orientation mapping by EBSP provided a considerable amount of information about the microtexture of partially or fully recrystallized specimens.

Fig. 1. Experimental procedure.

Table 1. Chemical composition of investigated steel. (mass%)

C	Si	Mn	P	Al
0.0024	0.13	0.22	0.072	<0.001

2. Experimental Procedure

2.1. Sample Preparation

Figure 1 shows the method of processing the test materials. The chemical composition of the steel is given in Table 1. An ingot of this material was reheated to 1200°C and hot-rolled to 2.2 mm in thickness. The hot-rolled steel sheets were cold-rolled at a reduction of 77% to 0.5 mm in thickness, intermediate-annealed at various temperatures from 540 to 700°C for 30 s in an Ar atmosphere, and second cold-rolled at a 12% reduction to 0.44 mm in thickness. Final annealing was carried out at 800°C for 30 s in an Ar atmosphere. To simulate continuous annealing, the heating rates in intermediate and final annealing were adjusted to 10°C/s.

The intermediate annealing temperature of the ordinary two-stage cold rolling method in the manufacturing process for electrical steel is above 700°C.³⁾ To compare the one-stage and two-stage cold rolling methods, a one stage cold-rolling method specimen was prepared by 80% cold rolling reduction of the hot-rolled sheet to 0.44 mm in thickness, followed by final annealing at 800°C.

2.2. Investigation Procedure

The progress of recrystallization during intermediate annealing was observed by optical microscope. The recrystallized fractions of the intermediate-annealed sheets were determined by the cross-section method using optical micrographs. The final annealed sheet textures were measured by pole intensity and (100) pole figures using the X-ray diffraction method. The magnetic induction B_{50} of final-annealed sheets was measured by the ring core method.

The microtexture of the intermediate annealed sheets and the microtextural changes during final annealing were investigated by EBSP. The spacial resolution of EBSP is less than 0.5 μm . Electron back scattering patterns were captured by CCD camera and analyzed automatically by the Hough transform.⁸⁾ This system was developed by Adams *et al.* as "Orientation Imaging

Fig. 2. Method of investigating microtextural changes during final annealing.

Microscopy (OIM)".⁵⁻⁷⁾ The EBSP measurements on the 1.5 μm pitch hexagonal grid gave a 2-dimension crystalline orientation map in an area of approximately 200 $\times$ 300 μm .

Figure 2 shows the procedure used to investigate microtextural changes during final annealing. The specimens with and without second cold rolling were annealed in sequence at 650, 680, and 710°C. After each annealing, EBSP measurements were performed in the same area of the specimens. This method made it possible to trace the changes in microtexture with the progress of recrystallization and grain growth during final annealing.

3. Results

3.1. Progress of Recrystallization during Intermediate Annealing

Figure 3 shows the effects of the intermediate annealing temperature on the recrystallized fraction. Recrystallization started with annealing above 600°C, and the recrystallized fraction increased as the intermediate annealing temperature increased. The sheet intermediate-annealed at 700°C had completely recrystallized. Figure 4 shows an optical micrograph of the sheet intermediate-annealed at 640°C. It consists of small equiaxed recrystallized grains and elongated deformed grains. The recrystallized fraction was estimated to be 60%.

3.2. Texture and Magnetic Property of Final-annealed Sheet

Figure 5(a) shows the effects of the intermediate annealing temperature on the final-annealed sheet texture. Intermediate annealing at 640°C gave the maximum value of (100) pole intensity in the final-annealed sheet. This was due to {001}<210> texture development, as shown in Fig. 5(b).

Figure 6 shows the effects of the intermediate annealing temperature on the ring core magnetic induction B_{50} . The sheet intermediate-annealed at 640°C gave the

Fig. 3. Effects of intermediate annealing temperature on recrystallized fraction.

Fig. 4. Optical micrograph of sheet intermediate-annealed at 640°C.

maximum magnetic induction, which was much higher than that of the specimens produced by one-stage cold rolling or ordinary two-stage cold rolling. It is well known that the $\{001\}$ texture improves the circumferential magnetic property.^{1,9)} Therefore, the superior ring core magnetic induction obtained by intermediate annealing at 640°C is understood to be caused mainly by $\{001\}\langle 210 \rangle$ texture development.

3.3. Microtexture of Intermediate-annealed Sheet

When the intermediate annealing temperature was 640°C, the $\{001\}\langle 210 \rangle$ texture was enhanced after final annealing. Therefore, the origin of the $\{001\}\langle 210 \rangle$ texture is assumed to exist in the sheet intermediate-annealed at 640°C.

Figure 7 shows the microtexture of the sheet intermediate-annealed at 640°C as measured by EBSP. The bold and light lines indicate boundaries whose misorientations θ between nearest measurement points are $2^\circ < \theta < 15^\circ$ and $15^\circ < \theta$, respectively. Small equiaxed recrystallized grains and elongated deformed grains can be observed in Fig. 7(a). The elongated grains have small misorientation boundaries because of their gradual crystalline orientation change in the grain interior. The $\langle 110 \rangle // \text{RD}$, $\langle 111 \rangle // \text{ND}$, $\langle 100 \rangle // \text{ND}$, and $\{001\}\langle 210 \rangle$ area are colored red, green, yellow, and blue respectively in Figs. 7(b) and 7(c). These figures indicate that most of recrystallized grains have the $\langle 111 \rangle // \text{ND}$ orientation, and most of the deformed grains have the $\langle 110 \rangle // \text{RD}$ orientation. Some $\{001\}\langle 210 \rangle$ recrystallized grains can be observed in crowds of recrystallized grains, and some $\{001\}\langle 210 \rangle$ deformed areas can be seen close to the α -fiber deformed area.

Fig. 5(a). Effects of intermediate annealing temperature on final-annealed sheet texture.

Fig. 5(b). (100) pole figure of final-annealed sheet whose intermediate annealing temperature was 640°C.

Fig. 6. Effects of intermediate annealing temperature on ring core magnetic induction B_{50} .

3.4. Microtextural Changes during Final Annealing

To investigate the effect of second cold rolling on the final-annealed sheet texture formation, the microtextural changes during final annealing of specimens with and without second cold rolling were measured by EBSP.

Figure 8 shows the changes in microtexture during final

Fig. 7. Microtexture of sheet intermediate-annealed at 640°C.

Red: Area whose angle between $\langle 110 \rangle$ and RD is less than 10° . Green: Area whose angle between $\langle 111 \rangle$ and ND is less than 15° . Yellow: Area whose angle between $\langle 100 \rangle$ and ND is less than 15° . Blue: Area whose misorientation between $\{001\} \langle 210 \rangle$ is less than 10° . Bold line: Boundary whose misorientation θ is $\theta \geq 15^\circ$. Light line: Boundary whose misorientation θ is $15^\circ > \theta \geq 2^\circ$.

Fig. 8. Changes in microtexture during final annealing. (second cold rolling reduction rate, 0%)

Green: Area whose angle between $\langle 111 \rangle$ and ND is less than 15° . Yellow: Area whose angle between $\langle 100 \rangle$ and ND is less than 15° . Bold line: Boundary whose misorientation θ is $\theta \geq 15^\circ$. Light line: Boundary whose misorientation θ is $15^\circ > \theta \geq 2^\circ$.

Fig. 9. Changes in microtexture during final annealing. (second cold rolling reduction rate, 12%)

Green: Area whose angle between $\langle 111 \rangle$ and ND is less than 15° . Yellow: Area whose angle between $\langle 100 \rangle$ and ND is less than 15° . Bold line: Boundary whose misorientation θ is $\theta \geq 15^\circ$. Light line: Boundary whose misorientation θ is $15^\circ > \theta \geq 2^\circ$.

annealing of the specimen without second cold rolling. EBSD measurements were done in the same area to trace the local orientation changes after each annealing. Since the recrystallized fraction after annealing at 650°C is the same as that of the intermediate-annealed sheet, it can

be considered that the microtexture after annealing at 650°C is that of the intermediate-annealed sheet. After annealing at 680°C, recrystallization is almost complete. Most recrystallized grains in the sheet annealed at 680°C have the $\langle 111 \rangle // \text{ND}$ orientation, which is the typical

recrystallization texture of cold-rolled steel.¹⁰⁾ Comparing Figs. 8(a) and 8(b), it may be concluded that one of the major origins of $\langle 111 \rangle // \text{ND}$ grains in the final-annealed sheet is the recrystallized grains that nucleated during intermediate annealing.

Figure 9 shows the changes in microtexture during final annealing of the specimen with second cold rolling. Comparing Figs. 9(a) and 9(b), some $\langle 100 \rangle // \text{ND}$ recrystallized grains, such as (p) and (q) in Fig. 9, nucleated in deformed grains after annealing at 680°C and grew into both deformed grains and small $\langle 111 \rangle // \text{ND}$ recrystallized grains. Consequently, they became coarse grains and dominated the overall texture after annealing at 710°C.

4. Discussion

The mechanism of $\{001\}\langle 210 \rangle$ texture formation in two-stage cold rolling is schematically illustrated in Fig. 10. The details of this mechanism will be discussed in this chapter.

4.1. Microtexture of Intermediate-annealed Sheet

The intermediate-annealed sheet, whose recrystallized fraction is 60 %, mainly consists of $\langle 111 \rangle // \text{ND}$ recrystallized grains (X in Fig. 10) and $\langle 110 \rangle // \text{RD}$ deformed grains (Y in Fig. 10). $\langle 110 \rangle // \text{RD}$ deformed grains, whose misorientation between the $\langle 110 \rangle$ direction and the rolling direction is less than 10°, is estimated to be 83 % of the deformed area. As will be discussed in the next paragraph, the $\{001\}\langle 210 \rangle$ deformed areas are considered to be origins of the $\{001\}\langle 210 \rangle$ texture after final annealing in the two-stage cold rolling method. Some $\{001\}\langle 210 \rangle$ deformed areas, whose misorientation between the $\langle 110 \rangle$ direction in the $\{001\}\langle 210 \rangle$ crystal and the rolling direction is estimated to be about 18°, exist close to the α -fiber, but they are a minor component in the intermediate-annealed sheet.

4.2. Changes in Microtexture during Final Annealing

1) Specimen without Second Cold Rolling

When second cold rolling is not performed, $\langle 111 \rangle // \text{ND}$ recrystallized grains grow into deformed area during final annealing. Consequently, recrystallization in deformed area, whose recrystallization temperature is higher than

that of γ -fiber,^{11,12)} is suppressed, and $\langle 111 \rangle // \text{ND}$ grains become main component after final annealing. This texture evolution has been reported by W. B. Hutchinson as the primary recrystallization texture development in cold-rolled steel sheets.¹⁰⁾

2) Specimen with Second Cold Rolling

When second cold rolling is performed, the growth of $\langle 111 \rangle // \text{ND}$ recrystallized grains into deformed area during final annealing is suppressed. This is because second cold rolling decreases the stored energy difference between $\langle 111 \rangle // \text{ND}$ recrystallized grains and deformed grains. In addition, $\langle 111 \rangle // \text{ND}$ grains no longer recrystallize during final annealing. Then, $\langle 111 \rangle // \text{ND}$ recrystallized grains are replaced by newly recrystallized $\{001\}\langle 210 \rangle$ grains (Z in Fig. 10) which nucleated in deformed area. The strain in $\langle 111 \rangle // \text{ND}$ recrystallized grains stored by second cold rolling makes newly recrystallized $\{001\}\langle 210 \rangle$ grains grow into $\langle 111 \rangle // \text{ND}$ recrystallized grains areas.

Many previous investigations concluded that the recrystallization mechanism in metals with low strain is strain-induced grain boundary migration (SIBM), and at higher strains, the SIBM mechanism is replaced by a mechanism in which recrystallized grains nucleate at heterogeneities in deformed grains.^{13,14)}

In the present study, the second cold-rolling reduction was small, and the specimen before second rolling was partially recrystallized. Therefore, it is possible that the nucleation of $\{001\}\langle 210 \rangle$ recrystallized grains during final annealing is caused by one of the following mechanisms.

(1) SIBM: SIBM of grains which were recrystallized during intermediate annealing.

(2) Nucleation: Nucleation at heterogeneities in deformed grains which were made by the first cold rolling. As shown in Fig. 9, the newly recrystallized grains, such as (p) and (q), nucleated in deformed areas. Therefore, it can be concluded that the second mechanism, nucleation at heterogeneities, works in $\{001\}\langle 210 \rangle$ texture formation in the two-stage cold-rolling method. $\{001\}\langle 210 \rangle$ nuclei can make high angle boundaries with both $\langle 110 \rangle // \text{RD}$ deformed grains and $\langle 111 \rangle // \text{ND}$ recrystallized grains. This makes it possible for the $\{001\}\langle 210 \rangle$ nuclei to grow into α -fiber deformed areas and $\langle 111 \rangle // \text{ND}$ recrystallized grains.

5. Conclusions

The recrystallization texture formed in the two-stage cold rolling method used to produce non-oriented electrical steel was investigated.

(1) When the recrystallized fraction of intermediate-annealed sheet is 60 %, the $\{001\}\langle 210 \rangle$ texture is enhanced in the final-annealed sheet. This $\{001\}\langle 210 \rangle$ texture development results in a superior circumferential magnetic property.

(2) The intermediate-annealed sheet mainly consists of $\langle 111 \rangle // \text{ND}$ small equiaxed recrystallized grains and $\langle 110 \rangle // \text{RD}$ elongated deformed areas. $\{001\}\langle 210 \rangle$ deformed areas exist close to $\langle 110 \rangle // \text{RD}$ deformed areas.

(3) During final annealing after second cold rolling,

Fig. 10. Mechanism of $\{001\}\langle 210 \rangle$ texture formation in two stage cold rolling method.

{001}<210> grains nucleate in deformed grains and grow into <111>ND small recrystallized grains. Consequently, {001}<210> grains dominate the overall texture of the final-annealed sheet.

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