JMEPEG (1995) 4:401-412

Texture of Primary Recrystallization on Nonoriented Electrical Steel Sheet with Phase Transformation

T. Kumano, T. Kubota, and N. Takahashi

The magnetic properties of nonoriented (NO) electrical steel sheet are commonly improved if the texture of their products possesses "cube texture" (e.g., {100} ⟨0vw⟩, "goss texture" (i.e., {110}⟨011⟩, and less {222} texture. Industrially "cube type" has not been obtained, but "goss texture" has been. In a greater or lesser degree, {222} texture exists. To improve "goss texture" and reduce {222} texture, the grain size of the material prior to cold rolling should be larger. When the grain size before cold rolling is larger, during primary recrystallization, "goss texture" is enriched, {222} texture is decreased, and the grain grows so easily that higher induction and lower core loss can be obtained. This does not depend on the presence of phase transformation. In case of NO steel with phase transformation, heat treatment before cold rolling has been done below the austenite transition temperature (Ac_1) in order to prevent the fine grain size caused by $\alpha \rightarrow \gamma(+\alpha) \rightarrow \alpha$ transformation. By using material that was heated over Ac_1 and cooled with changing cooling rates, this study describes (a) the relationship between textures before cold rolling and the texture of the final product, and (b) the development of the magnetic properties.

Keywords

electric steels, recrystallization, texture

1. Introduction

ELECTRICAL steel sheet is classified into two types: nonoriented (NO) electrical steel sheet and grain-oriented electrical steel sheet (GO). From the point of view of metallurgical principles, GO is produced by "secondary recrystallization." GO is mainly used as a core material for static equipment (e.g., transformers), and NO steel is mainly used as a core material for rotating machines (e.g., motors and generators).

Furthermore, from the point of view of metallurgical characteristics, NO steel is classified into two types: with and without phase transformation. The existence of the phase transformation mainly depends on silicon content. "Low grade NO" steel has a phase transformation and low silicon content. On the other hand, "high grade" has high silicon content and does not have phase transformation (Fig. 1).

Because NO steel is mainly used as a core material for rotating machines, cube and goss textures that have ⟨100⟩, the axes of easy magnetization for iron and iron alloys parallel with the rolling direction should be developed, and {222} textures, which have the axes of hard magnetization, should be reduced to obtain better magnetic properties. The method of obtaining the cube texture was investigated very thoroughly, but it was not industrially obtained.

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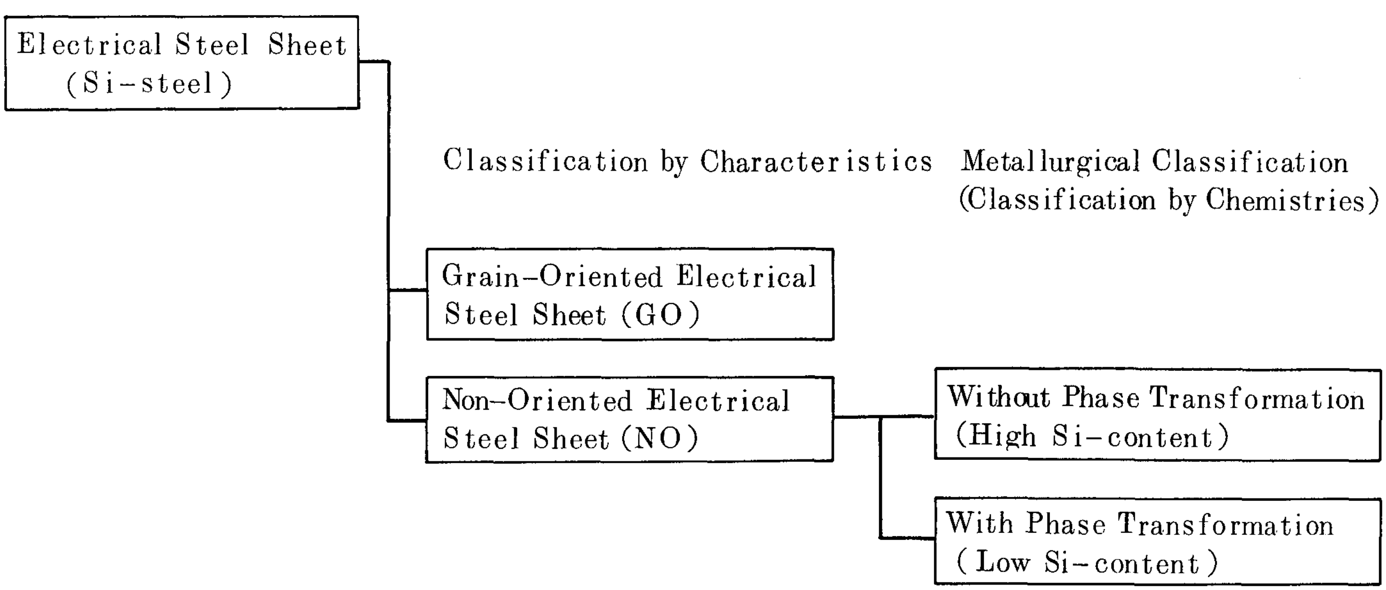

Fig. 1 Classification of electrical steel sheet

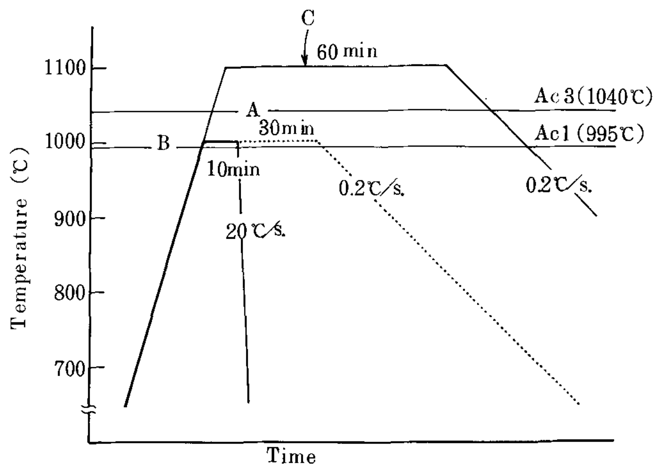

Fig. 2 Experimental procedure

Table 1 Chemical composition

Element	Composition, mass%
C	0.0029
Si	0.25
Mn	0.32
P	0.071
Al	0.27
N	0.0013

Table 2 Experimental procedure

Materials	Hot-rolled sheet in the factory, 2.6 mm
Heat treatment	Condition A, 1000 °C × 30 min → 0.2 °C/s
Heat treatment	Condition B, 1000 °C × 10 min → 20 °C/s
Heat treatment	Condition C, 1100 °C × 60 min → 0.2 °C/s
Cold rolling	2.6 mm → 0.50 mm (81%)
Final annealing	800 °C × 30 s

On the other hand, goss texture has been obtained industrially, and NO steel has, in greater or lesser degree, {222} texture. To gain the goss texture, reduce {222} texture, and enlarge the grain size, you must enlarge the grain size before cold rolling (Ref 1). Therefore, before cold rolling, the heat treatments of NO steel are mainly done to enlarge the grain size. If the grain size before cold rolling is larger, during primary recrystallization, "goss texture" is enriched and {222} texture is decreased. The grains grow quite easily; thus higher induction and lower core loss can be obtained. This does not depend on the presence of phase transformation.

However, in the case of "with phase transformation," heat treatment has been done below the Ac_1 before cold rolling to prevent the fine grain size caused by $\alpha \rightarrow \gamma(+\alpha) \rightarrow \alpha$ phase transformation. Therefore, even if it is annealed over Ac_1, magnetic properties are not improved. Therefore, it seems that NO steel may be the limit for the improvement of magnetic properties.

To overcome the limit, we planned to use the phase transformation. That is, if the annealing temperature of hot band is just over Ac_1, the texture would not be randomized, but would remain as "cube." Furthermore, if the cooling rate is so low, grain would grow during cooling. As a result, "cube texture" and "large grain" could be obtained after hot-band annealing. This better influences the texture and the structure of the final product.

Concerning NO steel with phase transformation, this study discusses the relationships among the texture, the grain size of the material before cold rolling, and primary recrystallization. In addition, the development of the magnetic properties is described.

2. Experimental Procedure

2.1 *Material*

Specimens were prepared from one hot-rolled sheet, which was normally hot rolled to a thickness of 2.6 mm in the α region in the factory. Their chemical compositions are described in Table 1. They contain 0.25% Si, 0.27% Al, low C and low N, and possess phase transformation.

2.2 *Procedure*

The experimental procedure is described in Table 2 and Fig. 2. The specimens were annealed at the stage of hot band as follows:

- Condition A: 1000 °C × 30 min → 0.2 °C/s
- Condition B: 1000 °C × 10 min → 20 °C/s
- Condition C: 1100 °C × 60 min → 0.2 °C/s

After that, they were pickled and cold rolled from 2.6 to 0.50 mm (reduction rate: 81%) and annealed at 800 °C for 30 s. (Note that the Ac_1 and Ac_3 of this material are 995 and 1040 °C, respectively, when the heating rate is 1.0 °C/s.)

2.3 *Investigation*

The following were investigated:

- Microstructure before cold rolling (but after hot-band annealing) and after final annealing
- Texture before cold rolling (but after hot-band annealing) and after final annealing: (a) {100} pole figure, (b) Normal direction axis density (from inverse pole figure)
- Precipitates observation with electron microscope before cold rolling
- Nonuniform distortion with full width half maximum intensity (FWHM) by using reflection of x-ray diffraction of specific planes (Stokes and Wilson method, Ref 2)
- Magnetic properties—W15/50 (W/kg) and B50 (T)—measurements with SST (□55 × 55 mm single sheet tester)

3. Results and Discussion

3.1 *Microstructure*

Figure 3 shows microstructures before the material was cold rolled (i.e., after hot-band annealing). Conditions A and C show the same aspects. That is, the mean grain size is rather large, around 500 μm. On the other hand, the mean grain size of con-

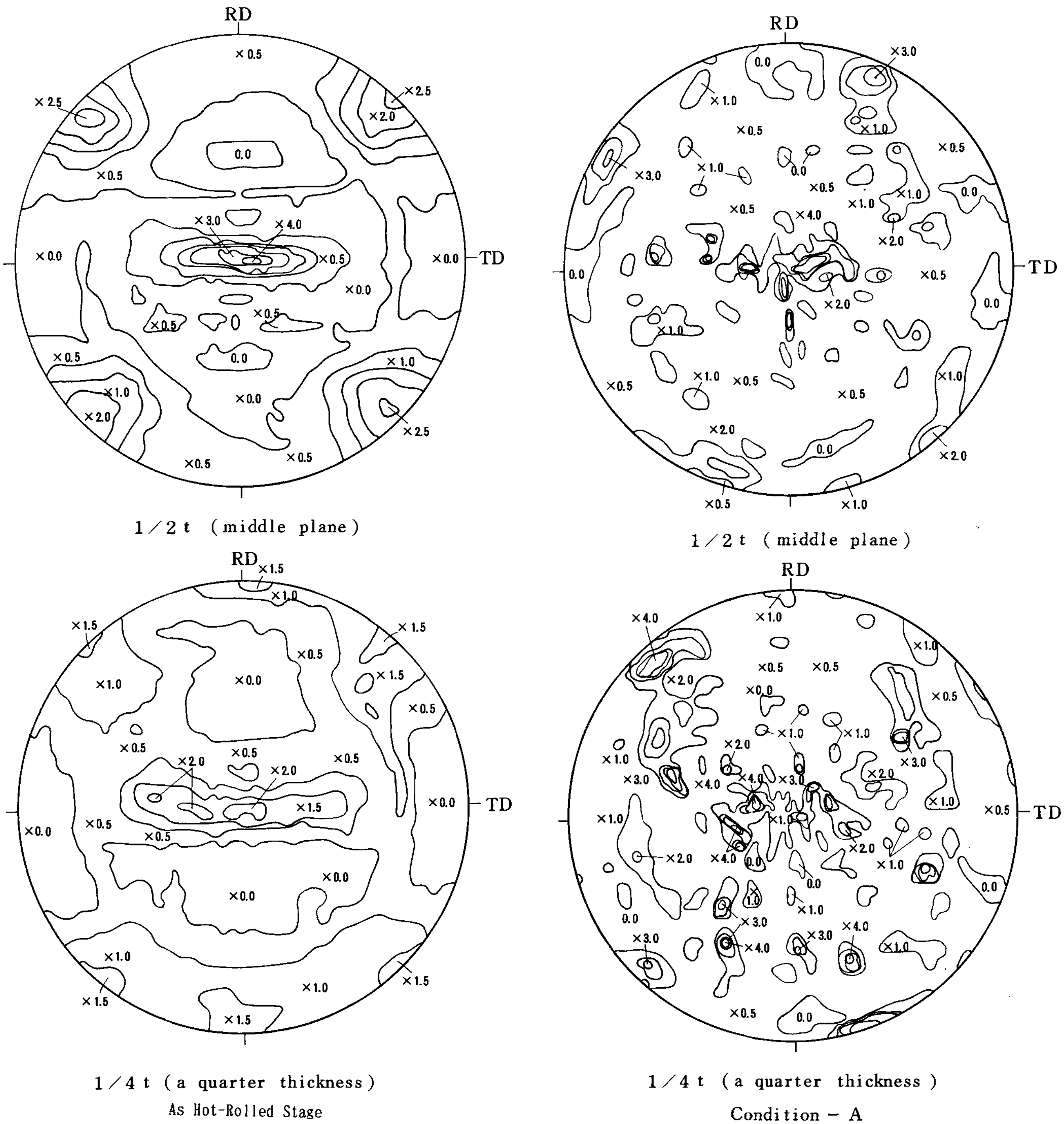

Fig. 3 Microstructures of the steel before cold rolling

dition B is relatively small, around 100 μm. The cause is the difference in the cooling rate through Ar_1. In conditions A and C, due to the slow cooling rate (and higher Ar_1 caused by lower cooling rate), grains grew sufficiently after phase transformation, $\gamma(+\alpha) \rightarrow \alpha$. In condition B, due to the higher cooling rate (and lower Ar_1 caused by higher cooling rate), grains did not grow significantly.

3.2 *Texture before Cold Rolling (after Hot-Band Annealing)*

Figure 4 shows {100} pole figures of sheets at 1/2 t and 1/4 t positions through the thickness before cold rolling. In conditions A and B, the texture is rather strong {100}⟨011⟩. On the other hand, in condition C, the texture is somewhat random. In addition, these

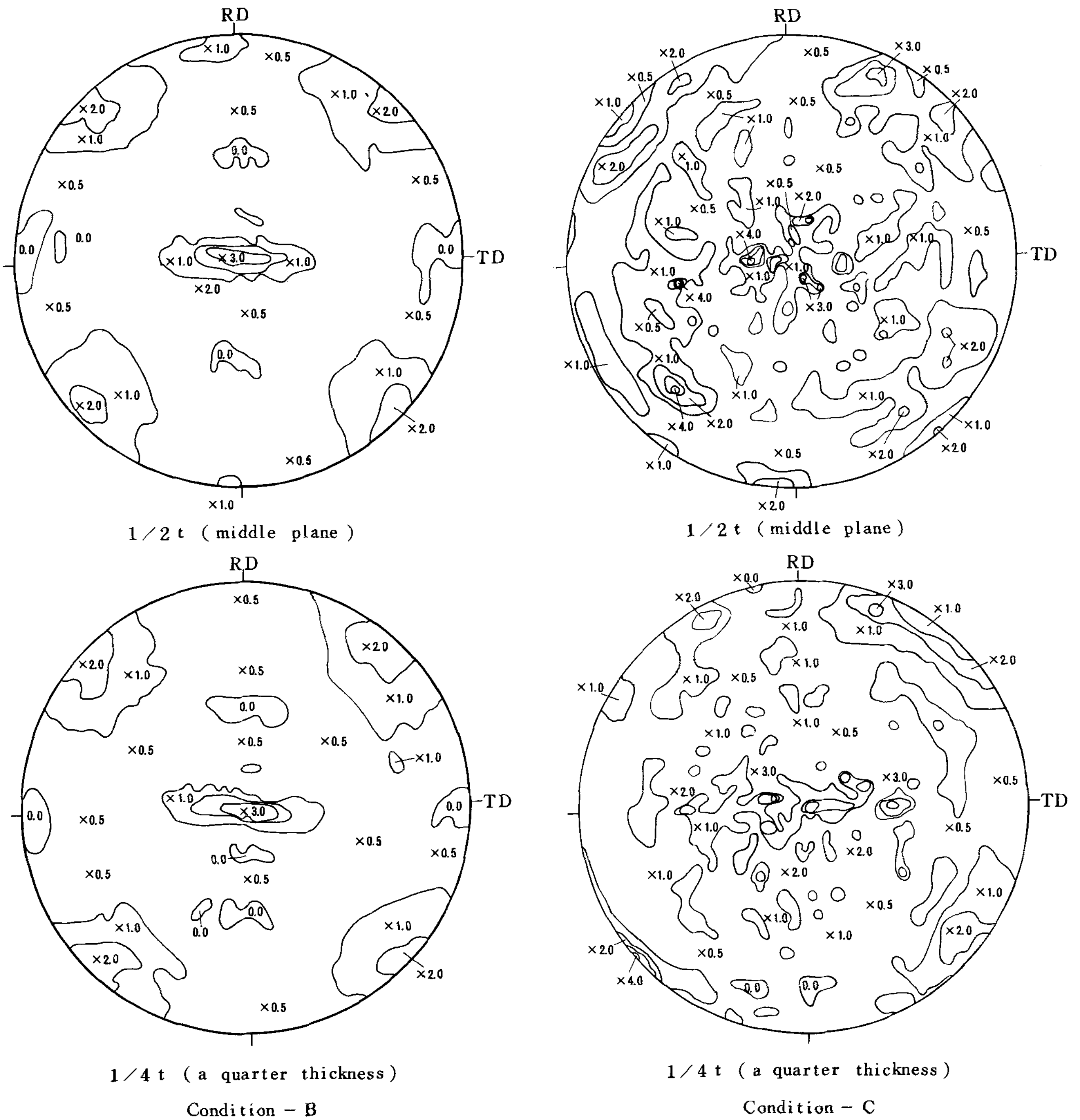

Fig. 3 Microstructures of the steel before cold rolling

pole figures show that the grain sizes of conditions A and C are rather large compared with those of condition D.

Figure 5 shows normal direction axis density from inverse pole figures (Fig. 6 to 8). The results are similar to {100} pole figures.

Conditions are summarized as follows. (a) Conditions A and B show strong {200} especially diagonal cube {100}⟨011⟩. Furthermore, in condition A, although the grain size is rather large, {200} is strong. (b) Condition A shows very weak {222}. (c) Condition C is randomized.

On the other hand, as conditions A and B were annealed for less time and at lower temperatures (at 1000 °C) in ($\alpha + \gamma$) region compared with condition C, the hot-band texture ({100}⟨011⟩) (Fig. 4) remains considerable. In addition, in condition A, because the cooling rate is as slow as in condition C, after retransformation (in α region), α grain grew significantly.

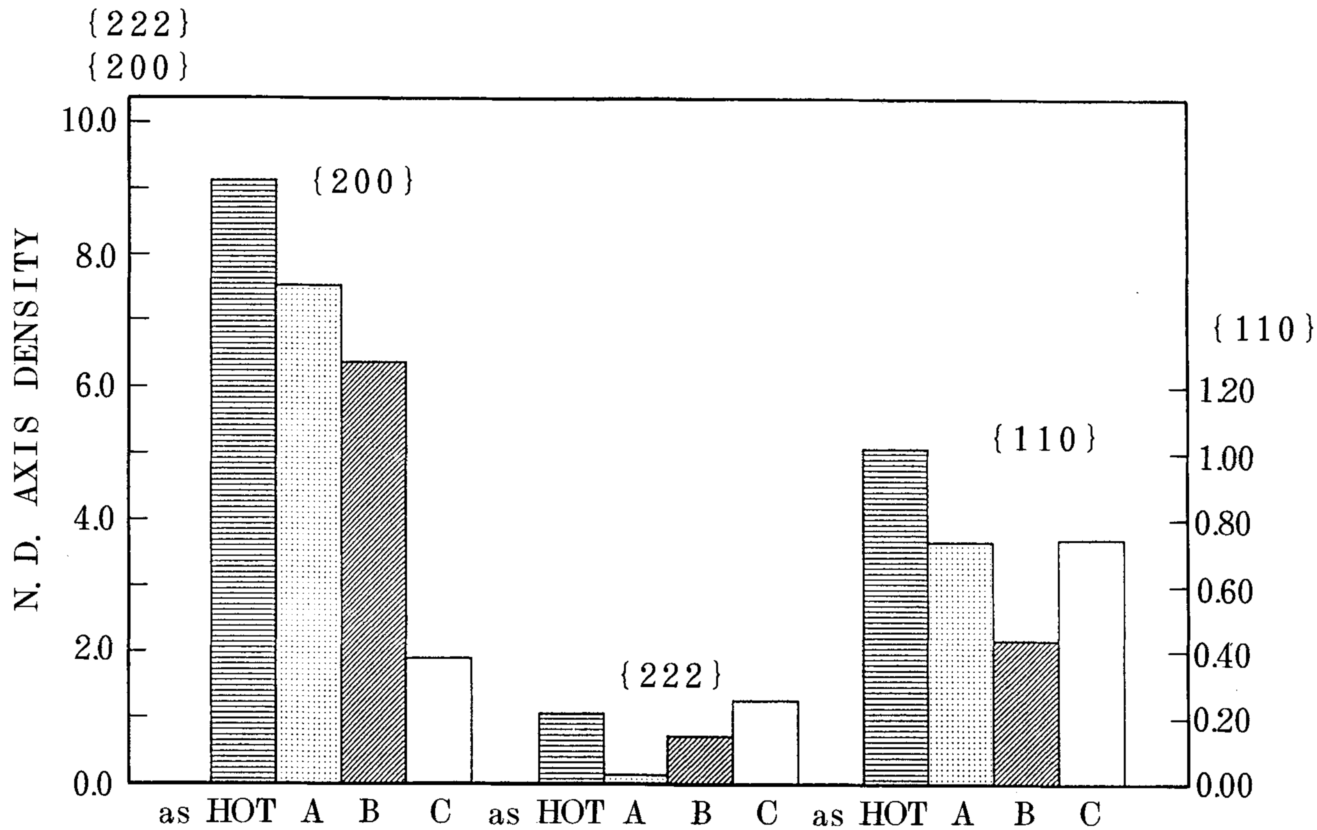

Fig. 4 Texture of steel before cold rolling—{100} pole figure

3.3 *Precipitates Observation*

Figure 9 shows the precipitates with electron microscope at 1/4 thickness position before cold rolling. The specimens were prepared by the deposit replica method. In conditions A and B, the sizes of precipitates are approximately 0.2 μm. On the other hand, in condition C, precipitate is approximately 0.02 μm, which is finer than ones in conditions A and B.

This difference could be caused by the hot-band-annealing temperature. In conditions A and B, as the annealing temperature was 1000 °C, the features of precipitates were similar to those after hot rolling. However, in condition C, as the temperature was 1100 °C, the precipitates at the hot-rolled stage could have dissolved during hot-band annealing and could precipitate finer again during cooling. Precipitates were mainly complexes of MnS and AlN.

3.4 *Microstructure after Final Annealing*

Figure 10 shows microstructure after final annealing. The grain size in condition A is largest (around 100 μm), and the one in condition C is second largest. The one in condition B is the smallest.

This could be caused by the grain size and the size of precipitates before the cold-rolling stage. In condition A, because the grain size before cold rolling was larger than in condition B and the size of precipitates was coarser than in condition C, the grains grew during final annealing more easily than in conditions B and C. As a result, the grain size after final annealing would be largest. In condition C, the grain size before cold rolling was as large as in condition A, but the size of precipitates was finer than in condition A. Therefore, in condition C, the grain size was smaller than in condition A.

Table 3 Nonuniform distortion

Condition	Distortion, $\times^{-3}$ Plane 110	Plane 200	Plane 222
A	10.6	6.2	6.0
B	13.6	10.4	5.8
C	13.3	9.6	4.2

Note: $\beta = 2 \cdot \eta \tan \theta$. β is integral breadth (rad). 2η is nonuniform distortion. 2θ is Bragg angle.

In addition, comparing conditions A and B, the grain size of the material before it is cold rolled could be more effective to the grain growth of primary recrystallization than the size of the precipitates.

3.5 *Texture of Final-Annealed Sheets*

Figure 11 shows {100} pole figures of final-annealed sheets at 1/2 t and 1/4 t positions through the thickness. In condition A, {222} is weak, and goss texture {100}⟨001⟩ has developed significantly. At the 1/2 t position, the plane near {200} texture has also developed. In condition B, at the 1/4 t position, the texture is similar to the texture of A, but at the 1/2 t position, the plane near {222} has developed. In condition C, goss texture

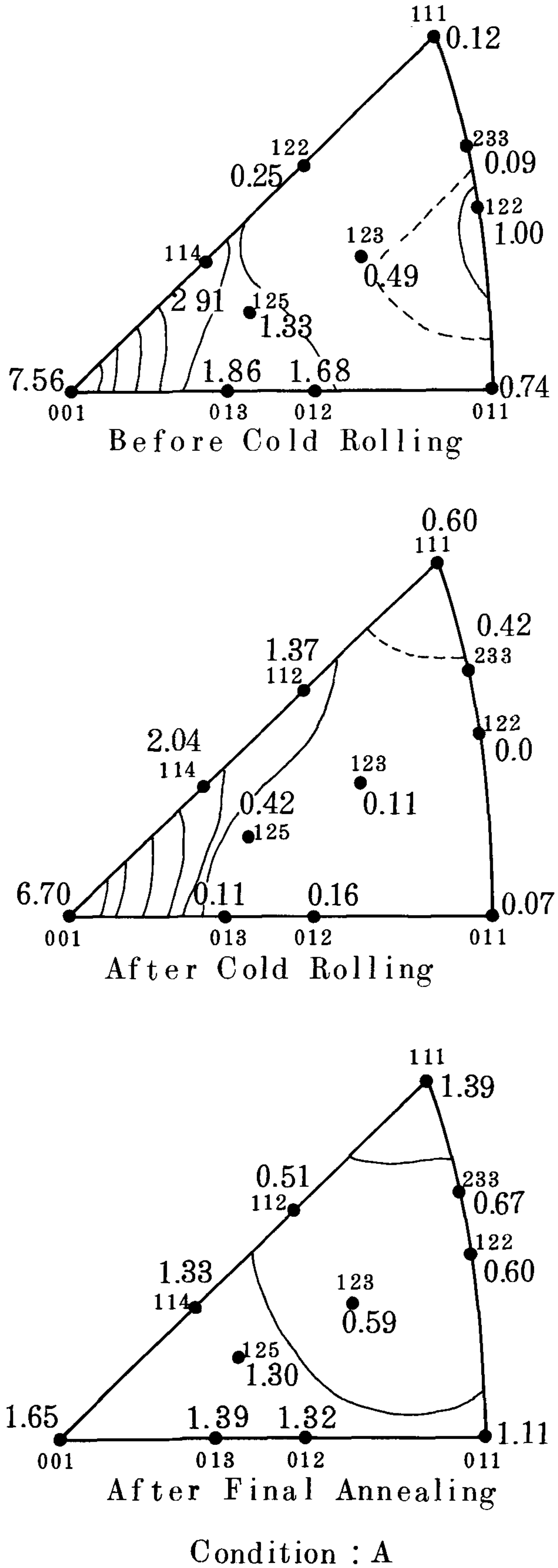

Fig. 5 Normal direction axis density from inverse pole figures before cold rolling

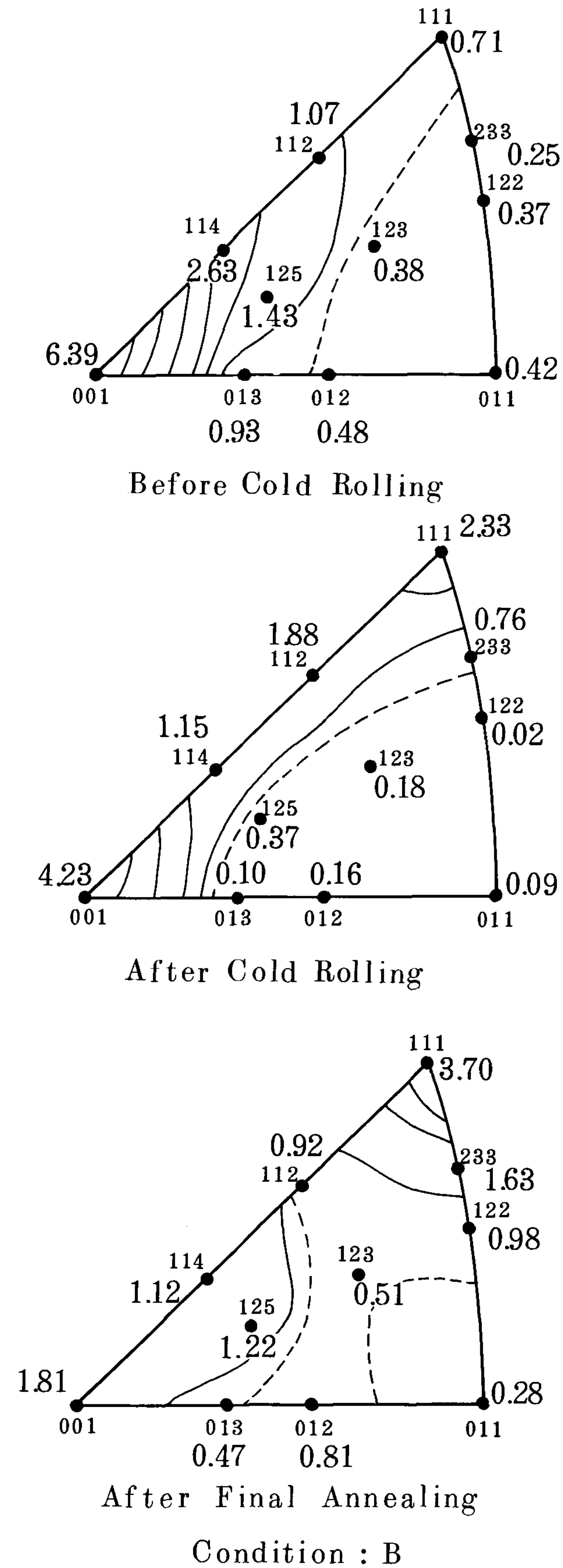

Fig. 6 Inverse pole figure (ND)

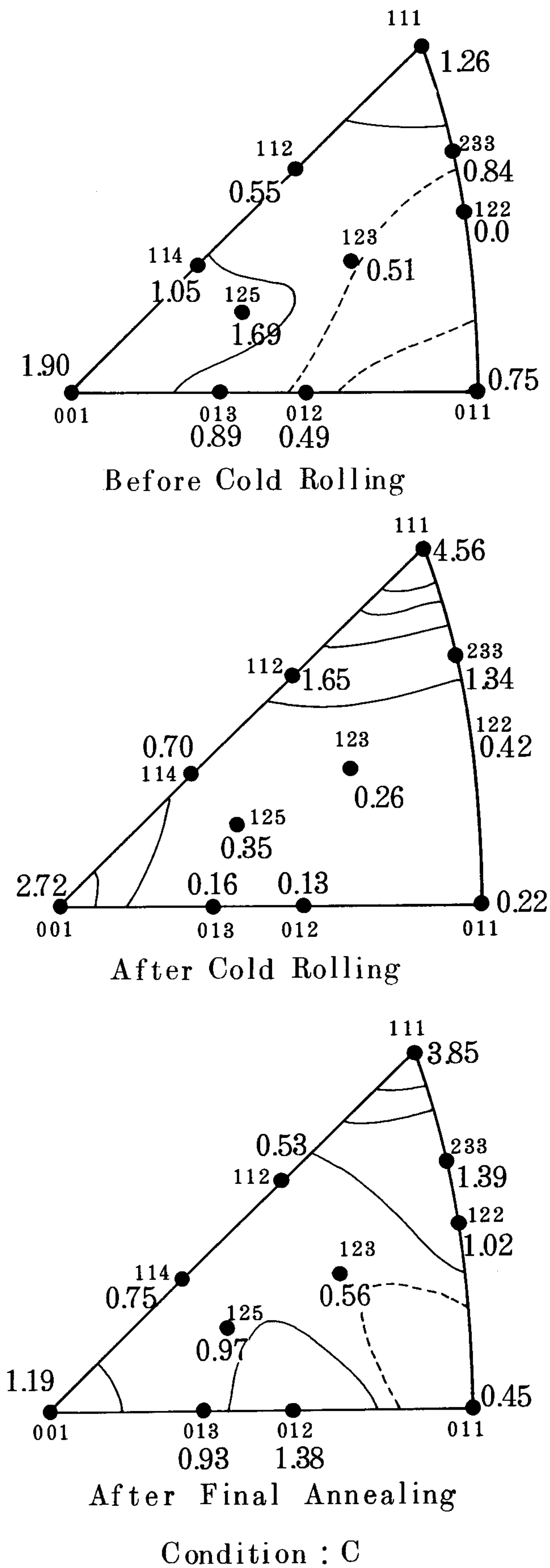

Fig. 7 Inverse pole figure (ND)

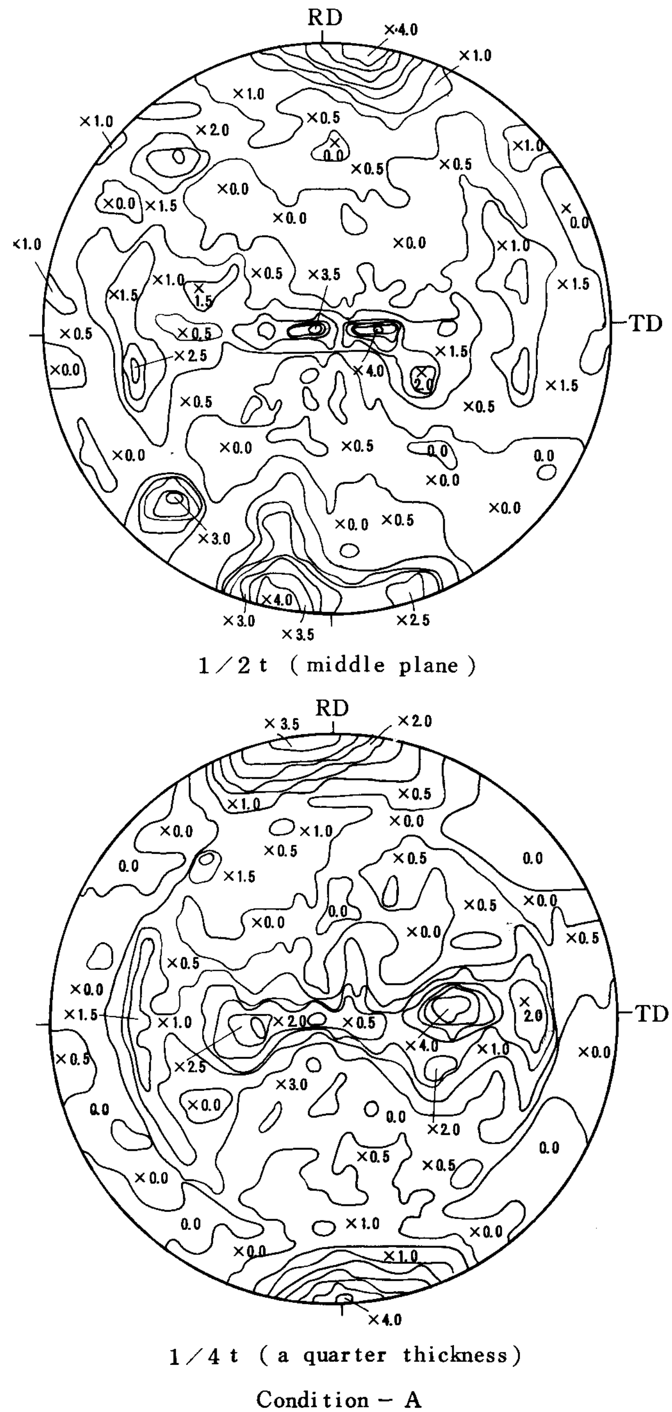

Fig. 8 Inverse pole figure (ND)

{100}⟨001⟩ has developed, and the plane of {222} has developed significantly.

Figure 12 shows normal direction axis density from inverse pole figures (Fig. 6 to 8). The results are similar to {100} pole figures. In condition A, the density of {222}, which deteriorates magnetic properties, is very weak. On the other hand, in conditions B and C, it is rather strong. In addition, in condition A, the density of {110}, which is preferable to magnetic properties, is stronger than B and C.

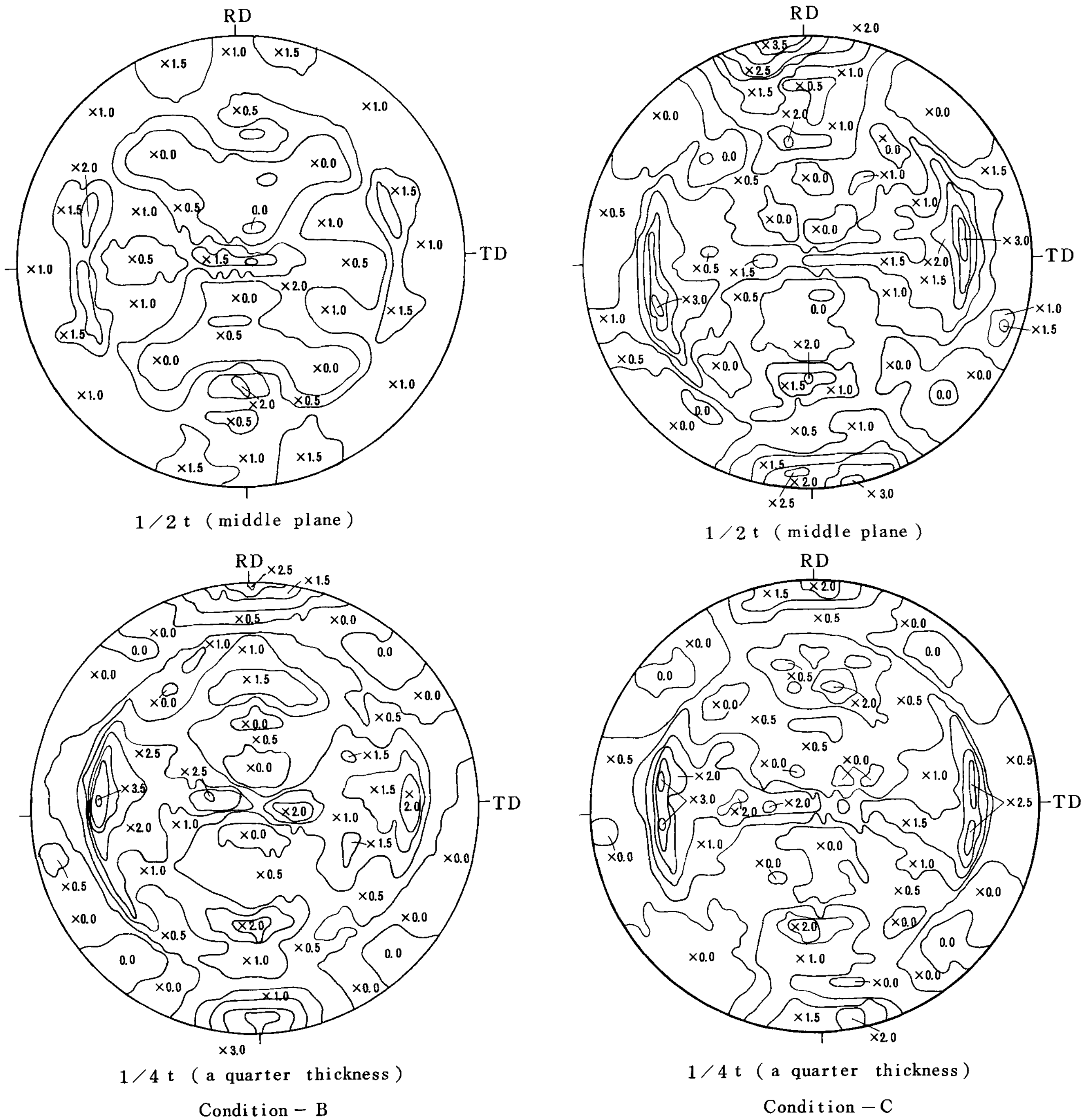

Fig. 8 Inverse pole figure (ND)

3.6 *Nonuniform Distortion and Texture after Final Annealing*

Nonuniform distortion after cold rolling was estimated with full width half maximum intensity (FWHM) of {110}, {200}, and {222} planes by XRD (Stokes and Wilson method, Ref 2) in order to estimate the strain energy.

Table 3 shows nonuniform distortion for {110}, {200}, and {222}. Using these data, the texture formation after final annealing is explained.

3.6.1 {110}

As for all conditions (A, B, and C), the nonuniform distortion of {110} is large and {110} nucleates more easily. Furthermore, as condition A had large grain size before cold rolling, condition A could have strong {110}.

3.6.2 {200}

First, the comparison between conditions A and B is discussed. Nonuniform distortion of {200} in condition B is larger

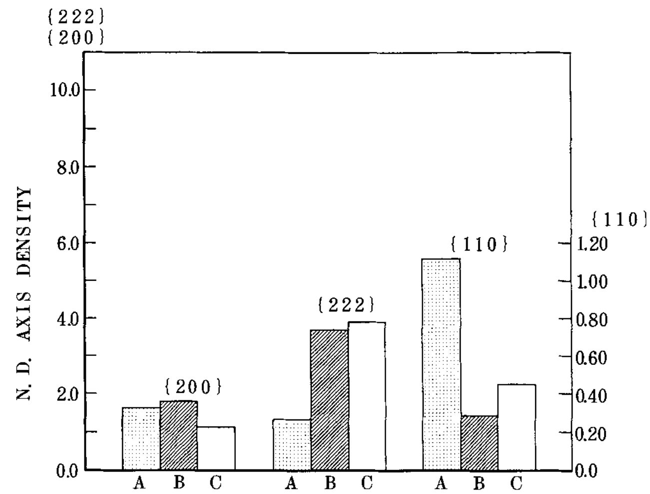

Fig. 9 Precipitates observation of the steel before cold rolling

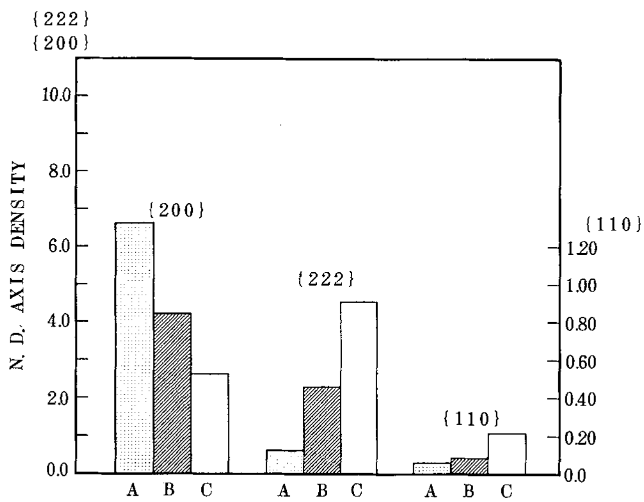

Fig. 10 Microstructures of the final-annealed steel

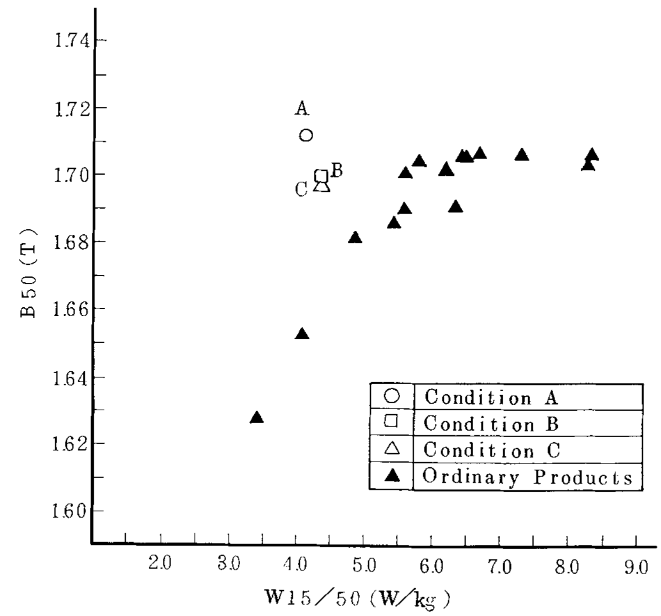

Fig. 11 Texture of the final-annealed steel

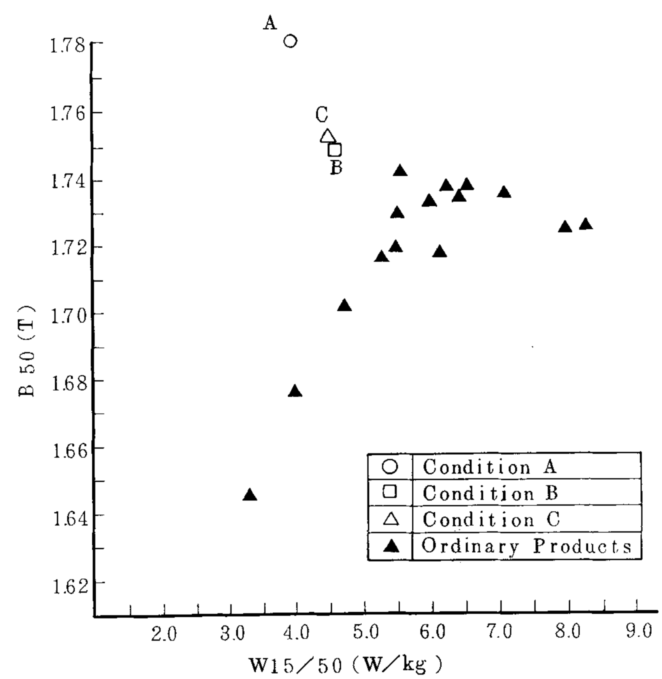

Fig. 12 Normal direction axis density from inverse pole figures of final-annealing stage

than the one in condition A. Therefore although the intensity of {200} in condition B was weaker than the one in condition A before cold rolling, the nucleation for {200} became easy. As a result, the intensities of {200} in conditions A and B texture after final annealing are comparable.

Second, concerning the comparison between conditions B and C, although the accumulated amount of distortion is comparable, {200} in condition B in the final-annealed texture was stronger than the one in condition C. This depends on the amount of {200} at before and after cold rolling (Fig. 5 and 13).

3.6.3 {222}

Although the nonuniform distortion among conditions A, B, and C does not differ very much, the big differences occurred in the final-annealed texture. A and B have different grain sizes (the area of grain boundary) before cold rolling. A and C have different amounts of {222} before and after cold rolling.

As a result, due to the effect of the multiplication of these two factors, that is, small amount of {222} and small strain energy of {222}, condition A has the weakest {222} after final annealing.

In this study, the size of crystallite was not considered because the reduction rate is so high (81%) that it could be negligible. The analysis was tried with the Hall (Ref 5) method, but accurate data could not be obtained, especially at high 2θ angle.

In addition, the results of this research are not always consistent with previous research (Ref 4, 5). To explain this differ-

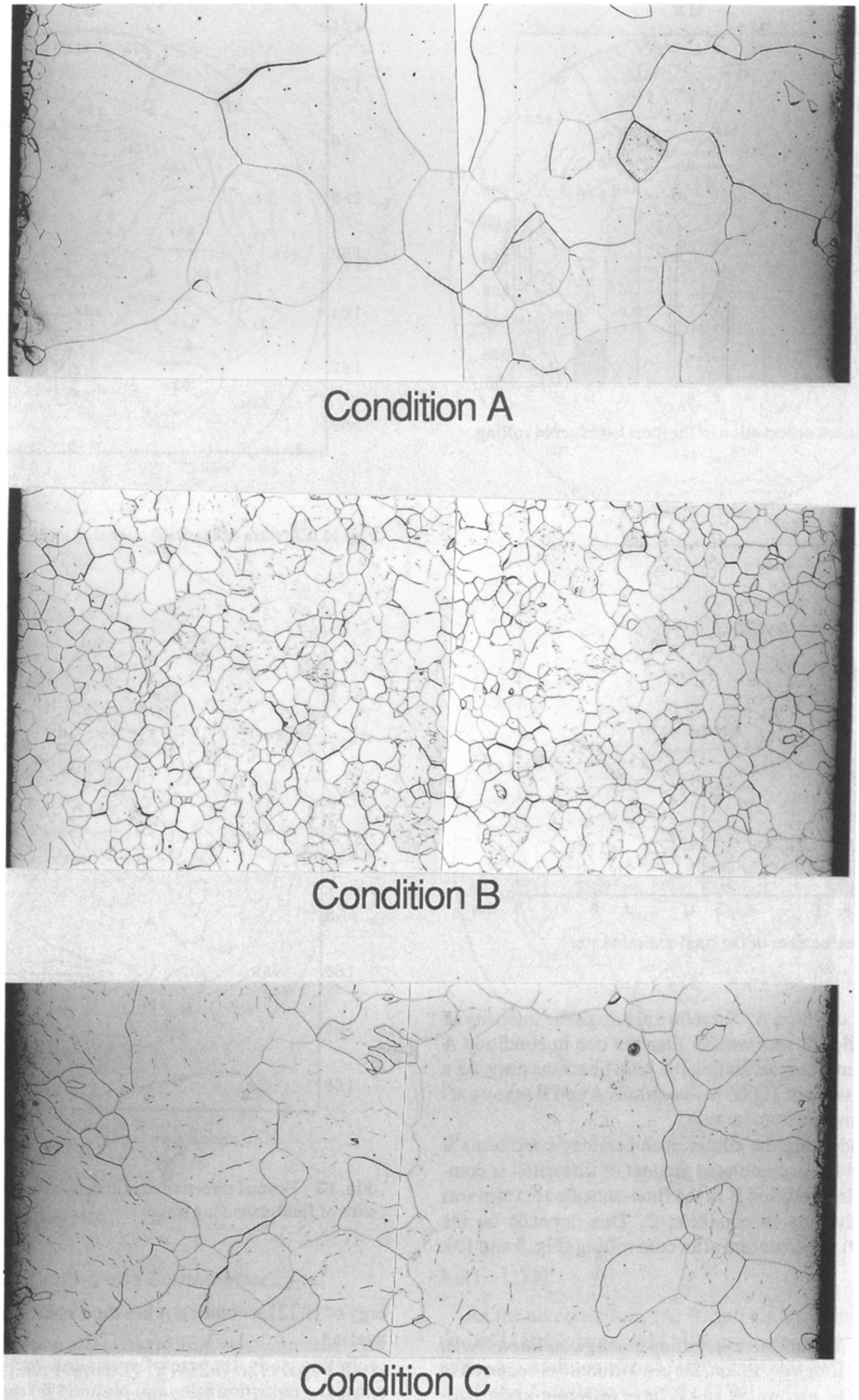

Fig. 13 Normal direction axis density from inverse pole figures of cold-rolling stage

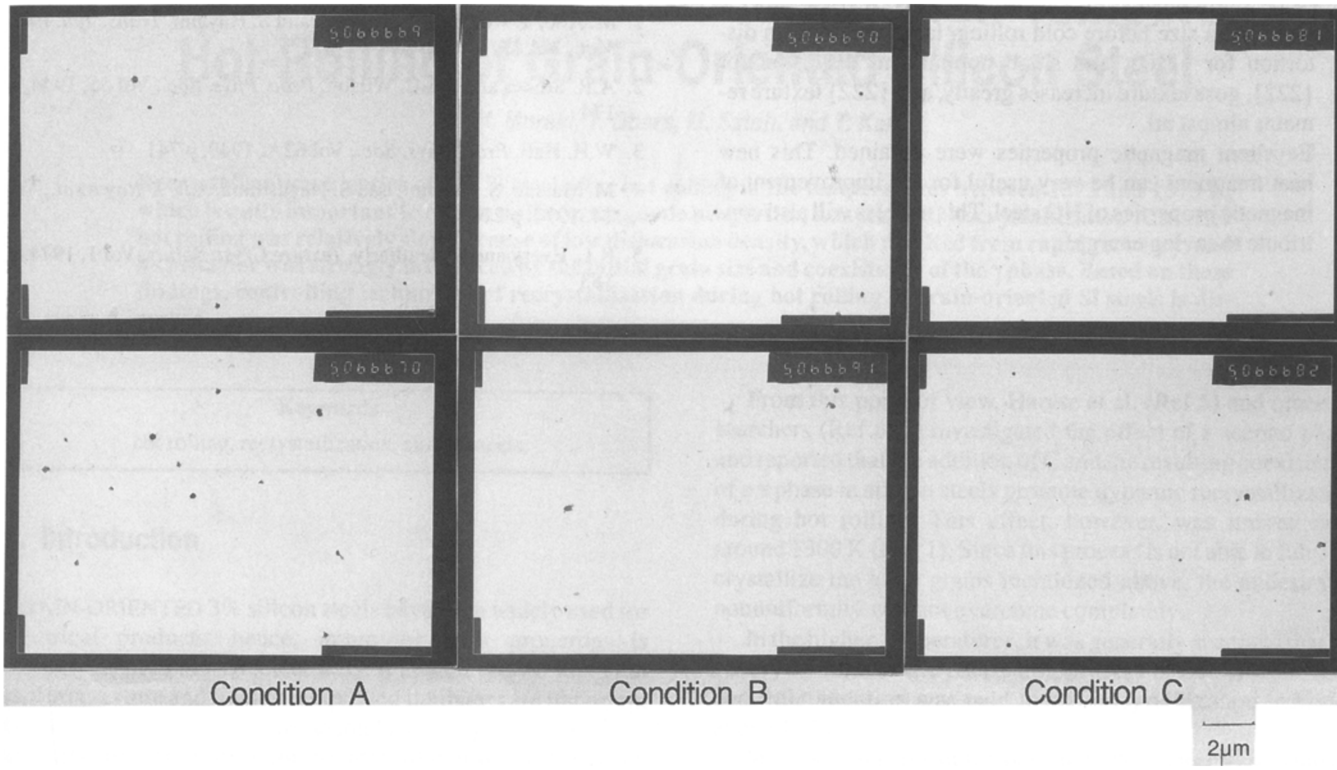

Fig. 14 Magnetic properties (average of each 22.5° direction) by single sheet tester

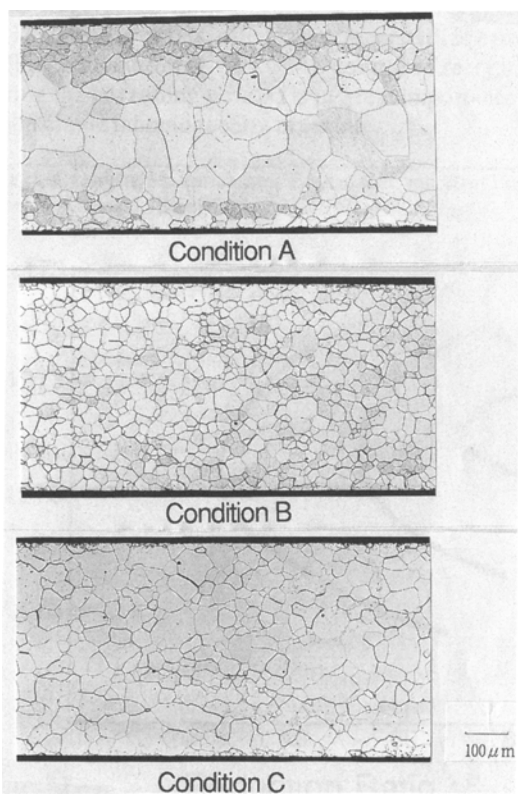

Fig. 15 Magnetic properties (average of L + C) by single sheet tester

ence, other factors (silicon content and precipitates) should be considered.

3.7 *Magnetic Properties—W15/50 (W/kg) and B50 (T)—Measurements*

Figures 14 and 15 compare the magnetic properties—W15/50 (W/kg) and B50 (T)—of our research with ones of ordinary products in the factory. They were measured with SST (□55 × 55mm single sheet tester) in the laboratory. The vertical axes indicate B50 (T) and induction at 5000 A/m, and the horizontal axes indicate W15/50 (W/kg) and core loss at 1.5 T and 50 Hz.

Figure 14 shows the average of each 22.5° direction for W15/50 and B50. Figure 15 shows the average of L + C (parallel and perpendicular to the rolling direction) for W15/50 and B50. Condition A indicates very good magnetic properties, which can be easily imagined from its texture.

4. Conclusions

- Concerning NO steel that undergoes phase transformation, (contrary to usual knowledge, the texture and grain size of a final-annealed product improve, even if it is annealed over Ac_1. As a result, magnetic properties improve significantly.
- These results were obtained by annealing over Ac_1 and under Ac_3 followed by slow cooling process. Concerning grain size, due to large grain size and coarse precipitates be-

fore cold rolling, grain size is large after final annealing. Concerning the texture, due to strong {200}, weak {222}, large grain size before cold rolling, large nonuniform distortion for {110}, and small nonuniform distortion for {222}, goss texture increases greatly, and {222} texture remains almost nil.

- Excellent magnetic properties were obtained. This new heat treatment can be very useful for the improvement of magnetic properties of NO steel. This process will also contribute to saving energy.

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