Texture Evolution during Recrystallization and Grain Growth in Heavily Cold-rolled Fe-3%Si Alloy

Masato YASUDA,1,* Takashi KATAOKA,2 Yoshiyuki USHIGAMI,3 Kenichi MURAKAMI1 and Kohsaku USHIODA4,5)


(Received on April 16, 2018; accepted on June 20, 2018; J-STAGE Advance published date: July 18, 2018)

Recrystallization and grain growth are important phenomena for controlling the mechanical and magnetic properties of steels through texture. Only a limited number of studies have been carried out on texture evolution during recrystallization and grain growth in heavily cold-rolled Si steel. The present study first focuses on clarifying the texture evolution during normal grain growth, followed by an investigation into the development of the {411}<148> component during recrystallization. The {411}<148> component is remarkably developed during normal grain growth after the completion of recrystallization. At just the commencement of recrystallization, differences in grain diameter of recrystallized grains in terms of crystal orientation were not detected. However, it is worthwhile to mention that the nucleation of {411}<148> recrystallized grains is unexpectedly fast in heavily cold-rolled Si steel. Recrystallized {411}<148> grains were observed to nucleate in the deformed α-fiber grains, especially near the grain boundaries. Nuclei with {411}<148> orientation grow easily due to the high mobility of the interface between the recrystallized/non-recrystallized grains and the high driving force. Consequently, the diameter of a {411}<148> recrystallized grain becomes relatively large upon the completion of recrystallization. This contributes to the selective grain growth during the normal grain growth stage because of the size effect.

KEY WORDS: recrystallization texture; grain growth; size advantage; nucleation; electrical steel sheet; Si steel; {411}<148>.

1. Introduction

Recrystallization and grain growth play an important role in controlling the mechanical and magnetic properties of steels through texture. For example, the <111>//ND fiber texture contributes to superior deep drawability, which is preferred for automobile applications,1,2) where ND denotes the normal direction. Meanwhile, the <100>//ND texture, including {100}<001>, improves the magnetic properties, which is preferred for non-electrical steel sheets.3–5) Texture development during recrystallization and grain growth is well known to be affected by the steel composition as well as the process parameters adopted for cold rolling reduction.

In low carbon steel sheets, particularly IF (Interstitial Free) steel, the {111}<uvw> component develops after recrystallization. {111}<uvw> grains preferentially nucleate in the vicinity of the prior grain boundaries and the interior of the {111}<uvw> deformed grains in the early stages of recrystallization.6,7) Although the recrystallized texture depends on the steel composition and process conditions, it is roughly classified based on the rolling reduction, especially cold rolling reduction. In the case of high reduction, the {111}<112> component develops8–10) whereas under 70% reduction, the {111}<110> component develops.11–13) Concerning texture evolution during grain growth, Hutchinson et al.14) and Suzuki et al.15) confirmed that the {111} texture developed in low carbon steel sheets due to the size advantage.

In the case of electrical steel sheets requiring low iron loss, Si is usually added to increase specific resistance and decrease eddy current loss. A decrease in thickness also causes a decrease in the eddy current loss, and therefore, high cold rolling reduction is preferred. It is generally...
believed that the \{111\}<112> and \{411\}<148> component develop after recrystallization in heavily cold-rolled Si steel.\(^{16-19}\) In terms of the change in texture during grain growth, Park et al.\(^{20}\) investigated texture evolution during grain growth in Fe-2\% Si alloy after low (75\%) cold rolling reduction. Goss and \{111\}<112> component developed after recrystallization. As grain growth advanced, these orientations decreased because the grains of these orientations were smaller than those of random orientation, namely size advantage. In this case, since the rolling reduction was low, the \{411\}<148> texture did not develop and the behavior of this orientation during grain growth was not clearly understood. Han et al.\(^{21}\) also investigated texture evolution during grain growth in heavily cold-rolled Fe-3\%Si alloy. The specimens were annealed at various temperatures to change the grain size. The specimen annealed at low temperature showed a strong \{111\}<112> component, and the specimen annealed at high temperature showed a strong \{411\}<148> component. However, it is not clear why the \{411\}<148> component significantly developed during grain growth.

The \{411\}<148> component often develops in heavily cold-rolled Si steel sheets, and this orientation is part of the \{h,1,1\}<1/h,1,2> fiber texture reported by Homma et al.\(^{22}\) It is worthwhile to mention that \{411\}<148> has a precise 29 relationship with the Goss orientation. For manufacturing grain oriented electrical steel, the distribution of the \{411\}<148> component along the rolling direction (RD) in the primary texture is believed to be crucial in preventing degradation of the magnetic flux density after secondary recrystallization of Goss grains. Recently, it has been recognized that the \{411\}<148> component plays an important role in the precise control of the secondary recrystallization of Goss grains.\(^{23}\)

The origin of the \{411\}<148> orientation has not yet been clarified. Homma et al.\(^{24}\) investigated into the origin of the recrystallization of \{h,1,1\}<1/h,1,2> in heavily cold-rolled bcc iron. They claimed that \{h,1,1\}<1/h,1,2> oriented recrystallized grains, including the \{411\}<148> component, recrystallize in the vicinity of the grain boundaries in \{100\}<011>-\{211\}<011> deformed \(\alpha\)-fiber grains. Quadir and Duggan\(^{25}\) reported that \{411\}<148> oriented grains recrystallized within \{100\}<011> deformed \(\alpha\)-fiber grains in 95\% cold-rolled IF steel sheets. Gobernado et al.\(^{26}\) also investigated the development of the recrystallization texture of IF steel sheets after cross cold rolling. Cross cold rolling was revealed to be an effective method to increase the intensity of \{411\}<148> orientation. The recrystallized grains with \{411\}<148> orientation are observed in the deformed \(\alpha\)-fiber grains such as \{100\}<011>. Against these studies, Zhang et al.\(^{27}\) claimed that \{211\}<011> deformed grains from the initial cube \{100\}<001>-\{100\}<012> grains are significant in terms of the nucleation sites of the \{411\}<148> recrystallized grains, while \{100\}<011> deformed grains do not act as a nucleation site of the \{411\}<148> recrystallized grains in heavily cold-rolled Fe-2.5\%Si alloy with mainly the columnar structure.

In heavily cold-rolled Si steel, the \{111\}<112> and \{411\}<148> component often develop after recrystallization, and the evolution of these orientations during grain growth strongly affects the magnetic property. However, there has been no systematic study on the texture evolution during recrystallization and grain growth in heavily cold-rolled Si steel.

Therefore, the present study aimed at clarifying the mechanism of texture evolution during recrystallization and grain growth in heavily cold-rolled Fe-3\%Si steel, with particular focus on the development of the \{111\}<112> and \{411\}<148> texture component.

### 2. Experimental Procedure

The starting material was a commercially processed hot annealed band of silicon steel. The thickness of the material was 2.8 mm, and it had the following chemical composition: 3.25 mass\% Si and 0.06 mass\% C. The material was cold-rolled to 0.3 mm thickness with 89\% reduction. The cold-rolled sheet was heated at the rate of 15\(^{\circ}\)C/s to various temperatures and then quenched without holding. For the specimens annealed at 830\(^{\circ}\)C, the specimens were held at this temperature for 0 to 30 min, and then quenched.

The annealed specimen was observed by an optical microscope along the transverse direction (TD). Vickers hardness (0.5 kg f) was measured in each annealed specimen by hardness tester (Mitsutoyo HM2011). Based on the results of microstructure and hardness measurements, the specimen annealed at 750\(^{\circ}\)C was confirmed to be fully recrystallized and was regarded as the specimen just before grain growth. The specimen annealed at 830\(^{\circ}\)C for 30 min was regarded as the specimen after grain growth.

Texture measurements were performed on the rolling plane at 1/10 thickness. The \{200\}, \{220\} and \{222\} pole figures were measured by X-ray diffraction (XRD) using Rigaku RINT 2500HF. The experimental data were processed to obtain the orientation distribution function (ODF).\(^{20}\) In this paper, the texture is represented by the \(\phi_2 = 45^\circ\) ODF section in Euler space. The texture, grain size, grain size distribution, and misorientation angle were measured by SEM-EBSD (HITACHI S4300, EDAX OIM DATE COLLECTION). All specimens for EBSD measure-

---

**Table 1.** Detailed measurement condition of XRD and EBSD for specimens before and after grain growth.

<table>
<thead>
<tr>
<th></th>
<th>Before grain growth 750(^{\circ})C for 0 min.</th>
<th>After grain growth 830(^{\circ})C for 30 min.</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>XRD</td>
<td>(\cdot)1/10 t layer</td>
<td>(\cdot)1/10 t layer</td>
<td></td>
</tr>
<tr>
<td>EBSD</td>
<td>Step size 1 (\mu)m</td>
<td>Step size 4 (\mu)m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\cdot)W400 (\mu)m (\times) L800 (\mu)m, 5 areas</td>
<td>(\cdot)W800 (\mu)m (\times) L2400 (\mu)m, 16 areas</td>
<td></td>
</tr>
</tbody>
</table>

- **Definition of the grain**
  - Grains > 3 points
  - Grain Boundary > 3 degree
  - Removal of grain on edges

© 2018 ISIJ

1894
ments were electropolished. Detailed measurement conditions for EBSD are listed in Table 1.

For the purpose of obtaining the information during recrystallization, the cold-rolled sheet was annealed to 620°C, 640°C, and 680°C at the rate of 15°C/s, and then quenched without holding. Thus, partially recrystallized specimens were prepared. EBSD measurement conditions for these specimens are also listed in Table 2.

3. Results

Figure 1(a) shows the change in Vickers hardness (0.5 kgf) and Fig. 1(b) shows the change in the optical microstructures of the TD cross section as a function of annealing temperature. The hardness remarkably decreased in the temperature range 400°C to 700°C due to recovery and recrystallization. The specimens annealed to above 700°C showed almost no change in hardness. Non-recrystallized grains were still observed in the specimen annealed to 700°C, whereas recrystallization was completed in the specimen annealed to 750°C. Grain growth was confirmed in the specimens annealed to 830°C and held for 30 min. Consequently, the specimens annealed to 750°C and annealed at 830°C for 30 min were considered as the ones just before and after grain growth, respectively.

Textures were measured by XRD and EBSD methods. The ODFs in the \( \phi_2 = 45^\circ \) section, as evaluated by XRD and EBSD, are shown in Fig. 2. The EBSD results before and after grain growth were averaged using the data in 5 and 16 areas, respectively. The EBSD data represented local area information, and the XRD data represented global area information. Almost no difference was observed in the main texture component. Therefore, the EBSD data obtained by the present procedure are suggested to be representative textures. The \( \{111\} <112> \) component developed in the

### Table 2. Measurement condition of EBSD for specimens during recrystallization.

<table>
<thead>
<tr>
<th>Partially recrystallized specimen</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>620, 640, 680°C for 0 min.</td>
<td></td>
</tr>
<tr>
<td>EBSD</td>
<td></td>
</tr>
<tr>
<td>-1/10 layer</td>
<td></td>
</tr>
<tr>
<td>-Step size 0.15 μm</td>
<td></td>
</tr>
<tr>
<td>-W400 μm × L800 μm, 5 areas</td>
<td></td>
</tr>
<tr>
<td>TD cross section</td>
<td></td>
</tr>
<tr>
<td>-Step size 0.15 μm</td>
<td></td>
</tr>
<tr>
<td>-W400 μm × L800 μm</td>
<td></td>
</tr>
</tbody>
</table>

![Fig. 1](image) (a) Changes in Vickers hardness and (b) optical micrographs in TD cross section as a function of annealing temperature.

![Fig. 2](image) Texture change during grain growth. (a) and (c): specimen before grain growth (750°C), (b) and (d): specimen after grain growth (830°C for 30 min) and (e): texture subtracted (c) from (d). Upper ODFs were obtained from XRD method and lower ODFs from EBSD method. (Online version in color.)
specimen during recrystallization (just after the completion of recrystallization), while the \{411\}<148> component devolved in the specimen during grain growth (after grain growth). Figure 2(e) shows the difference ODF subtracting ODF in Fig. 2(c) from ODF in Fig. 2(d), which means the texture change during grain growth. The \{411\}<148> component significantly increased, whereas the \{111\}<112> component decreased. Han et al.\textsuperscript{21)} also showed the same tendency obtained by XRD method. Since the ODF intensity obtained by XRD method was based on area intensity, it is insufficient to discuss the change in texture in terms of the number of the grains and the grain diameter. In contrast, those data could be obtained by EBSD method. Figure 3(a) shows the ODF based on the area intensity in the $\phi_2 = 45^\circ$ section using the data measured at all points, while Fig. 3(b) shows the ODF based on the grain number intensity in the $\phi_2 = 45^\circ$ section assuming 1 orientation per grain. The ODF in Fig. 3(c) is the square root of the area intensity (Fig. 3(a)) divided by the number intensity (Fig. 3(b)), which corresponds to the average grain diameter intensity. In this calculation, only the orientations with intensities larger than 1 are used, while intensities lower than 1 are considered to be 0. The intensity near the \{411\}<148> orientation exceeded 1.2, which was larger than that for any other orientations. Therefore, the grain diameter near the \{411\}<148> orientation is suggested to be relatively large.

Next, the diameters of the \{111\}<112> and \{411\}<148> grains were calculated from the orientation data measured by EBSD. The allowance angle was set to be less than 5 degree (Table 3). Among the 70 195 grains measured, 1 017 were \{111\}<112> grains and 671 were \{411\}<148> grains. On the other hand, the average diameter of the \{111\}<112> grains was 4.5 $\mu$m, whereas that of the \{411\}<148> grains was 5.2 $\mu$m. Figure 4 shows the diameter distribution of the \{111\}<112> and \{411\}<148> grains. Most of the \{111\}<112> grain ranged from 2 $\mu$m to 6 $\mu$m, while the \{411\}<148> grains were relatively large, with diameters of more than 6 $\mu$m.

Figure 5 shows the distribution of the misorientation angles between the \{111\}<112> or \{411\}<148> grains and their neighboring grains in the specimen just after the completion of recrystallization, \textit{i.e.}, before grain growth. The frequency of misorientation angles within 15 degree between the \{111\}<112> grains and their neighboring grains was approximately 22%, while that of the misorientation angles between the \{411\}<148> grains and their

Table 3. Number of grains and average grain diameter in the specimen before grain growth.

<table>
<thead>
<tr>
<th></th>
<th>All</th>
<th>{111}&lt;112&gt; &lt;5°</th>
<th>{411}&lt;148&gt; &lt;5°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of grains</td>
<td>70 195</td>
<td>1 017</td>
<td>671</td>
</tr>
<tr>
<td>Number frequency (%)</td>
<td>–</td>
<td>1.4</td>
<td>1.0</td>
</tr>
<tr>
<td>Average grain diameter ($\mu$m)</td>
<td>4.7</td>
<td>4.5</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Table 4. Number of grains and average grain diameter in the specimen after grain growth.

<table>
<thead>
<tr>
<th></th>
<th>All</th>
<th>{111}&lt;112&gt; &lt;5°</th>
<th>{411}&lt;148&gt; &lt;5°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of grains</td>
<td>30 057</td>
<td>253</td>
<td>646</td>
</tr>
<tr>
<td>Number frequency (%)</td>
<td>–</td>
<td>0.8</td>
<td>2.1</td>
</tr>
<tr>
<td>Average grain diameter ($\mu$m)</td>
<td>27.3</td>
<td>23.3</td>
<td>28.6</td>
</tr>
</tbody>
</table>

Fig. 3. Texture before grain growth. (a) ODF calculated from all points in measured area, (b) ODF calculated from number of recrystallized grains and (c) square root of the value calculated by dividing (a) by (b). (Online version in color.)

Fig. 4. Distribution of grain size in the specimen before grain growth. (Online version in color.)
The driving force of grain growth, a grain whose diameter is larger than the critical diameter, consumes the matrix grains, and a grain with a diameter smaller than the critical radius grows because the growth rate becomes positive. On the other hand, a low angle grain boundary within 15° misorientationally, a low angle grain boundary within 15° misorientationally, a low angle grain boundary within 15° misorientationally, a low angle grain boundary within 15° misorientationally, a low angle grain boundary within 15° misorientationally, a low angle grain boundary within 15° misorientationally, a low angle grain boundary within 15° misorientationally, a low angle grain boundary within 15° misorientationally, a low angle grain boundary within 15° misorientationally, an image quality value of a grain greater than 5 000. In addition to this definition, the deformed grains are divided into three types: (1) recrystallized grains for each orientation as a function of annealing temperature in the partially recrystallized specimen, (2) partially recrystallized specimens annealed at 620°C, 640°C, and 680°C were analyzed. Figure 6 shows the change in fraction recrystallized and the average grain diameters of recrystallized grains for each orientation as a function of annealing temperature in the partially recrystallized specimens. Recrystallized grains in partially recrystallized specimens are defined by a misorientation within a grain of less than 5 degree and an image quality value of a grain greater than 5 000. In addition to this definition, the deformed grains were individually removed. The fraction recrystallized in the specimen annealed at 680°C was 53%, and the average grain diameter of {411} < 148 > orientation was larger than that of {111} < 112 > orientation (Fig. 6(b)). However, in
the early stages of recrystallization at 620°C and 640°C, only a few \{411\} <148> grains recrystallized, their average diameter was similar to that of the \{111\} <112> grains. It is worthwhile to mention that the recrystallized grains with \{411\} <148> orientation, which are believed to undergo slow recrystallization, recrystallized as early as those with \{111\} <112> orientation in the heavily cold-rolled Si steel. Figure 7 shows the image quality and orientation maps in the TD cross section of the specimen annealed at 640°C (the fraction recrystallized 27%), where the average diameter of the \{411\} <148> grains was similar to that of the \{111\} <112> grains. Contrary to the claim by Zhang et al.\textsuperscript{27} that the average diameter of the \{411\} <148> grains was large at throughout recrystallization, the present study revealed that it was not necessarily large at the early stage of recrystallization but became large in the later stage of recrystallization. Figures 7(a) and 7(b) show the typical areas where the \{411\} <148> and \{111\} <112> recrystallized grains formed, respectively. Many \{411\} <148> recrystallized grains were located along the deformed grains with α-fiber texture, while the \{111\} <112> recrystallized grains were not located along the deformed grains and tended to form colony structures. The stored energy induced by rolling deformation depends on the crystal orientation. Consequently, different crystal orientations have different rates of recrystallization.\textsuperscript{34} In a bcc iron such as Fe-3%Si alloy, \{111\} //ND oriented deformed grains have high dislocation densities which provides many nucleation sites.\textsuperscript{35,36} Therefore, the \{111\} <112> grains recrystallized in the \{111\} //ND deformed grains by forming a colony structure.

The nucleation sites of the \{411\} <148> recrystallized grains are classified into two types, which are shown in Fig. 8. First, the \{411\} <148> recrystallized grains nucleated along the boundaries of the \{100\} <011> and \{211\} <011> α-fiber textured deformed grains, as shown in Fig. 8(a). Second, the \{411\} <148> recrystallized grains nucleated within the α-fiber deformed grains, such as the \{100\} <011> grains (Figs. 8(b) and 8(c)). However, the former type is dominant.

To evaluate the nucleation frequency of the \{411\} <148> and \{111\} <112> recrystallized grains in the areas neighboring to the deformed grains, the number of such recrystallized grains was counted. For the specimen annealed at 640°C, the results are shown in Fig. 9. In comparison to the \{111\} <112> grains, the number of recrystallized grains neighboring to the \{411\} <148> recrystallized grains is revealed to be small. This implies that the \{411\} <148> recrystallized grains tend to recrystallize along the areas neighboring to the deformed grains having α-fiber texture. In contrast, the number of recrystallized grains neighboring to the \{111\} <112> recrystallized grains was large, implying that the \{111\} <112> grains tend to recrystallize by forming colony structures. The \{411\} <148> recrystallized grains neighboring to the deformed grains are easy to grow, taking into account the fact that the driving force for nuclei to grow into deformed grains is high and the mobility of the interface between the recrystallized and non-recrystallized grains, which is discussed later, is high. Furthermore, the difference in the grain diameter of the recrystallized grains with \{111\} <112> and \{411\} <148> is expected to become prominent as recrystallization proceeds (shown in Fig. 6), owing to the fact shown in Fig. 9. Therefore, the average grain diameter of \{411\} <148> recrystallized grains just after the completion of recrystallization is indicated to be already large.
Figures 10(a) and 10(b) show the misorientation of the \{411\}<148> or \{111\}<112> recrystallized grains against their neighboring recrystallized grains, respectively. The frequency of the low-angle grain boundaries in the \{411\}<148> recrystallized grains was 13%, and that in the \{111\}<112> grains was 19%. This result indicates that the \{111\}<112> recrystallized grains have a tendency to neighbor to grains with almost same orientations. This supports the fact that the \{111\}<112> recrystallized grains formed a colony structure. On the other hand, the frequency of low-angle grain boundaries in the \{411\}<148> recrystallized grains was lower, which indicates that the grain boundary of \{411\}<148> recrystallized grain is easy to migrate owing to high mobility.

Regarding the nucleation sites of the \{411\}<148> recrystallized grains in heavily cold-rolled Fe-3%Si alloy in this study, many \{411\}<148> grains recrystallized along the grain boundaries neighboring to the deformed grains with \(\alpha\)-fiber texture such as \{100\}<011>–\{211\}<011>.

Fig. 8. EBSD data showing two types of nucleation of \{411\}<148> orientated grains in partially recrystallized specimen (640°C for 0 s). (a) \{411\}<148> grains colored as pink recrystallized along boundaries neighboring to deformed \{100\}<011> and \{211\}<011> grains in TD cross section. (b) \{411\}<148> recrystallized grains with arrow surrounded by non-recrystallized \{100\}<011> in TD cross section and (c) in ND cross section. (Deviation angle is within 15°). (Online version in color.)

Fig. 9. Number frequency of recrystallized grains neighboring to the recrystallized \{111\}<112> and \{411\}<148> grains in the specimen annealed 640°C. The number of the \{111\}<112> and \{411\}<148> grains was 2 230 and 1 660, respectively. (Online version in color.)

Fig. 10. Misorientation angle between (a) \{111\}<112> and (b) \{411\}<148> recrystallized grains against neighboring grains in the partially recrystallized specimen (640°C for 0 min). The number of the \{111\}<112> and \{411\}<148> grains was 2 230 and 1 660, respectively. (Online version in color.)
Gobenardo and Kestens\textsuperscript{16} claimed that \{411\} <148> oriented grains recrystallized within \{100\} <011> deformed grains, especially in the vicinity of the grain boundary. He et al.\textsuperscript{10} also claimed that \{411\} <148> oriented grains existed at the grain boundary of \{211\} <011> deformed grains. On the contrary, Takenaka et al.\textsuperscript{18} claimed that \{411\} <148> oriented grains recrystallized at the deformation twin in \{100\} <011> deformed grains. However, the carbon content in the present study is 0.06 mass\% and much higher than 0.018 mass\%C by Takenaka et al. Therefore, solute carbon or presumably carbides may change the deformation behavior, which also affects the recrystallization mechanism and texture evolution. It may have caused a change in the dominant nucleation sites of the \{411\} <148> recrystallized grains.

Therefore, it may be concluded that the \{411\} <148> recrystallized grains presumably nucleated in the deformed \(\alpha\)-fiber grains, especially in the vicinity of the grain boundaries of \(\alpha\)-fiber textured deformed grains and selectively grew during recrystallization owing to the high mobility of the interface and high driving force.

5. Conclusions

To clarify the mechanisms of texture evolution during recrystallization and grain growth in a heavily cold-rolled Fe-3% Si steel sheet, texture change during grain growth was first investigated. Then, texture evolution during recrystallization process was further investigated. From these studies, the following results were obtained.

- \{111\} <112> was the main texture component just after the completion of recrystallization. After grain growth, the \{411\} <148> component significantly developed.
- At the fully recrystallized stage, the diameter of the \{411\} <148> grains was already larger than that of the grains with any other orientations. Therefore, the \{411\} <148> grains selectively grows during normal grain growth owing to the size advantage. Besides this, the high mobility of the boundaries neighboring to the \{411\} <148> grains promote the selective growth.
- At the early stages of recrystallization, there was no difference in diameter between the \{411\} <148> and \{111\} <112> grains. The \{111\} <112> recrystallized grains formed a colony structure. In contrast, the \{411\} <148> recrystallized grains nucleated in the deformed \(\alpha\)-fiber grains with a high dislocation density. Therefore, the driving force for the \{411\} <148> grain growth was higher than that for \{111\} <112>. Consequently, the diameters of the \{411\} <148> grains became large upon the completion of recrystallization. Moreover, the interfaces of the \{411\} <148> recrystallized grains and non-recrystallized grains migrated more easily compared to those of the \{111\} <112> recrystallized grains owing to the high mobility of the interface with higher misorientation.

REFERENCES