Onset of Secondary Recrystallization in High Purity 3.3%Si Steel

Yasuyuki HAYAKAWA,* Takeshi OMURA and Takeshi IMAMURA

Steel Research Laboratory, JFE Steel Corporation, 1-Kawasakidori, Mizushima, Kurashiki, 712-8511 Japan.

(Received on March 6, 2014; accepted on June 18, 2014)

Possibility of the occurrence of secondary recrystallization in high purity material without containing inhibitor elements was investigated experimentally. Only in the sample with primary recrystallization annealing performed at 900°C, onset of secondary recrystallization was observed. The orientation of secondary recrystallized grains proved to be (110)[001] (Goss) orientation. It was also shown that normal grain growth was suppressed in the sample in which secondary recrystallization occurred. Narrow grain size distribution and strong texture accumulation were considered to help the stabilization of the matrix grains.

Texture development during secondary recrystallization in the absence of inhibitors was discussed based on proposed growth models. It was shown from Grain Boundary Character Distribution (GBCD) analysis that the High Energy (HE) boundary model was applicable to secondary recrystallization and the Solid State Wetting (SSW) model was applicable to normal grain growth. The HE boundary was related theoretically to high mobility through high grain boundary diffusion coefficient. It was considered that reducing impurity elements exerted inherent high mobility of the HE boundary and hence led to the onset of the secondary recrystallization.

KEY WORDS: grain-oriented electrical steel; secondary recrystallization; grain boundary; primary recrystallization; texture; inhibitor.

1. Introduction

The first industrial production of Grain-Oriented electrical steel (GO) was described at the beginning of the thirties.1) As well known, many important improvements have been applied since introduced in the production technology of GO. All existing technologies utilize the same metallurgical method to obtain a very strong Goss texture (110)[001] in the final products, i.e. the process of oriented secondary recrystallization guided by uniformly distributed precipitates called inhibitors.

The inhibitors play a fundamental role in controlling the movement of grain boundaries during the final annealing which actuates the selective secondary recrystallization process.

May and Turnbull2) in 1958 clarified the necessity of dispersed precipitates of MnS for secondary recrystallization to develop. They suggested a function of the precipitates to inhibit normal grain growth, and thus maintain the driving force for secondary recrystallization. Swift3) related the diffusion controlled coarsening of inhibitors to the onset of secondary recrystallization. This method using MnS inhibitor is still now applied in producing Conventional Grain-Oriented electrical steel (CGO).

Since the suggestion by May and Turnbull,2) so many experiments were done for seeking new kinds of inhibitors including sulfides nitrides carbides and or solute elements. For concrete example of inhibitors, VN by Fiedler,4) AlN by Taguchi and Sakakura5) and TiC, VN, NbC by Matsuoka6) and MnSe by Fiedler7) were reported.

Saito8,9) investigated extensively the effect of solute elements and found addition of Pb, Sb, Nb, Ag, Te, Se, and S was effective in the inhibition of normal grain growth and also improved magnetic property by higher accumulation toward Goss orientation in secondary recrystallization texture.

Among technologies cited above following technologies have been used in mass commercial production of High permeability Grain-Oriented steel (HGO). The production method of HGO10) was announced using AlN and MnS as inhibitors manufactured by one stage cold rolling method. Only in the specimen containing both AlN and MnS normal grain growth was inhibited and successfully secondary recrystallization was obtained.

Another production method of HGO11) was invented with cold-rolling reduction rate 60–70% which is slightly higher than the original two stage rolling method. This method utilizes MnSe and Sb as inhibitors manufactured by one stage cold rolling method. Only in the specimen containing both AlN and MnS normal grain growth was inhibited and successfully secondary recrystallization was obtained.

GO were mainly produced by the above three methods until mid 1990s. High temperature slab reheating over 1300°C is required to disperse fine precipitates as inhibitors in these methods. Heating of the slab to a high temperature requires higher equipment cost, and in addition, results in an increase in the quantity of scale produced during hot rolling. This leads to many problems such as a lower product yield and more complicated equipment maintenance. The invention of the low temperature slab reheating technology was one of the largest targets in the research and development.

In 1996 new production method of HGO was put in use by low slab reheating temperature as 1150°C through nitriding...
after decarburization annealing.\textsuperscript{12)} Nitriding forms A1N as an inhibitor in the heating stage of secondary recrystallization annealing.

Another problem involved in the methods using inhibitors is that these inhibitor constituents, if remaining after the final finish annealing, cause deterioration of the magnetic properties. For the purpose of eliminating these inhibitor constituents such as Al, N, B, Se and S, purification annealing is carried out for several hours in a hydrogen atmosphere at a temperature of at least 1100°C after completion of secondary recrystallization. However, purification annealing carried out at such a high temperature leads to problems of a lower mechanical strength of the steel sheet, bucking of the lower part of the coil, and a considerably lower product yield.

Therefore production of GO without using inhibitors has been strongly demanded. In this paper possibility of the occurrence of secondary recrystallization in high purity material which does not contain inhibitor elements, was investigated experimentally and mechanism to attain Goss texture development in high purity material was discussed.

2. Experiment Procedures

Vacuum melt laboratory ingot was prepared and its chemical composition is given in \textbf{Table 1}. Impurity elements are reduced as low as possible except for Si and Mn. These elements are not effective for the development of secondary recrystallization in the investigations by Saito.\textsuperscript{8,9)}

The ingot was hot-rolled to 2.6 mm after soaking at 1100°C for 20 minutes. The hot band was then annealed at 1000°C for 60 seconds and cold-rolled to final thickness 0.35 mm. Primary recrystallization annealing was performed in dry nitrogen atmosphere at temperatures ranging from 700°C to 1050°C for 60 seconds. Final annealing was carried out from room temperature to 850°C with a heating rate of 200°C/h and then heated to 1150°C with a heating rate of 2.5°C/h. One of the samples was directly given the final annealing after cold rolling without being performed recrystallization annealing.

Microstructures of primary recrystallized sheets and that of after final annealing were investigated by optical microscope. The cold-rolling texture, primary recrystallization textures as well as the textures after final annealing were investigated by the X-ray diffraction analysis, and Orientation Distribution Function (ODF)s were calculated using the discrete method by Pawlik\textsuperscript{13)} from {100}, {110} and {211} pole figures. Texture measurements were performed on a center layer of the sheet thickness.

In order to calculate Grain Boundary Character Distribution (GBCD), pairs of grain orientations were generated in proportion to the value of ODF (f(\textbf{g})), using the method proposed by Morawiec \textit{et al.}\textsuperscript{14)} Generated orientations were expressed in Euler angle and misorientation angle and axis were calculated from the pairs of generated orientations.

The validity of the statistical calculation of GBCD was tested previously\textsuperscript{15)} in the texture of HGO by comparing the result obtained from direct measurement using Electron Back Scattering Diffraction (EBSD).

3. Experimental Results

After the primary recrystallization annealing, all the samples were fully recrystallized.

Grain size of primary recrystallized grains versus annealing temperature of primary recrystallization annealing is demonstrated in \textbf{Fig. 1}. It is shown that grain grows as the recrystallization annealing temperature rises. Grain size and macrostructure after the final annealing are shown in \textbf{Figs.}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig1.png}
\caption{Grain size of the samples after the primary recrystallization annealing temperatures ranging from 700°C to 1050°C for 60 seconds.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig2.png}
\caption{Grain size of the samples after the final annealing. The primary recrystallization annealing at temperatures ranging from 700°C to 1050°C was performed before the final annealing. One of the samples was directly given the final annealing after cold rolling without being performed recrystallization annealing.}
\end{figure}

\renewcommand{\arraystretch}{1.2}
\begin{table}[h]
\centering
\caption{Chemical composition (mass% or ppm) of the vacuum melt laboratory ingot.}
\begin{tabular}{lcccccccc}
\hline
\textbf{C} & \textbf{Si} & \textbf{Mn} & \textbf{S} & \textbf{Al} & \textbf{Ti} & \textbf{Nb} & \textbf{N} & \textbf{P} & \textbf{O} \\
\hline
10 ppm & 3.3% & 0.08% & 4 ppm & 20 ppm & 6 ppm & 10 ppm & 10 ppm & 20 ppm & 11 ppm \\
\hline
\end{tabular}
\end{table}
2 and 3 respectively. One of the samples in Figs. 2 and 3 was directly given the final annealing after cold rolling without being performed recrystallization annealing.

After the final annealing, only the specimen with primary recrystallization annealing at 900°C underwent a secondary recrystallization with grain diameter more than 10 mm as demonstrated in Fig. 3. Other specimens showed normal grain growth up to diameter of several hundred microns. Orientations of secondary recrystallized grains for the specimen with primary recrystallization annealing at 900°C measured by back-reflection Laue diffraction method at an interval of 2 mm are given in Fig. 4.

As shown in Fig. 4 the orientation of secondary recrystallized grains has Goss orientation. Deviation angle distributions from ideal Goss orientation around ND, TD and RD axis for the specimen with primary recrystallization annealing at 900°C are given in Fig. 5. Most of secondary recrystallized grains have deviation angle less than 13°. Average deviation angles around ND, TD and RD axis are 5.8°, 5.3° and 4.9° respectively. These deviation angles are larger than those in HGO but comparable to CGO.16)

The ODFs of the samples before and after final annealing are shown in Fig. 6. One of the samples was directly given the final annealing after cold rolling without being performed recrystallization annealing. The cold rolled sample which is without primary recrystallization annealing has α-fiber texture (RD//<110>) and the main component of primary recrystallization textures is γ-fiber texture (ND//<111>). After final annealing, the main component of primary recrystallization textures is enhanced except for the sample with primary recrystallization annealing at 900°C.

An additional experiment was done in order to observe grain growth behavior before the onset of secondary recrystallization. Primary recrystallized sheets prepared by the present experiment were isothermal annealed at 850°C for 50 hours with a heating rate of 200°C/h. Grain size of primary recrystallized sheet and that after isothermal annealing at 850°C for 50 hours are demonstrated in Fig. 7. After isothermal annealing, in the sample with primary recrystallization annealing at 900°C or 1050°C, normal grain growth was almost suppressed. After the final annealing, the sample without primary recrystallization annealing and the sample with primary recrystallization annealing at 700°C have larger grain sizes than the sample with primary recrystallization annealing at 900°C. It follows that normal grain growth is observed under 900°C of primary recrystallization annealing temperature. Microstructures of the samples with primary recrystallization annealing at 700°C and 900°C are given in Fig. 8. As shown in Fig. 8, grain size of the sample annealed at 700°C is smaller (average 10.2 μm) than that annealed at 900°C (average 37.8 μm). It is to be noted that the grain size of the sample annealed at 900°C is much larger than GO using inhibitors, in which primary recrystallized grain size is usually 10 μm.2) Colonies of small grains illustrated by the circle in Fig. 8 is recognized in the sample annealed at 700°C.

Grain size distribution of the samples with primary recrystallization annealing was performed at (a) 700°C, (b) 900°C (c) 1000°C before the final annealing, and (d) recrystallization annealing was omitted.

![Fig. 3](image-url)  
Macrostructure of the samples after the final annealing. The recrystallization annealing was performed at (a) 700°C, (b) 900°C (c) 1000°C before the final annealing, and (d) recrystallization annealing was omitted.

![Fig. 4](image-url)  
Orientations of secondary recrystallized grains for the specimen with primary recrystallization annealing at 900°C measured by back-reflection Laue diffraction method at an interval of 2 mm expressed by (100) and (110) pole figures.
recrystallization annealing at 700°C and 900°C obtained using image analyzing software is given in Fig. 9. In Fig. 9 the frequency is calculated by area fraction and the grain

Fig. 6. The cross-section of ODFs (Φ2=45°) of the samples before and after the final annealing. One of the samples was directly given the final annealing after cold rolling without being performed recrystallization annealing.

Fig. 7. Grain size of primary recrystallized sheet and that after isothermal annealing at 850°C for 50 hours.

Fig. 8. Microstructure of the sample with primary recrystallization annealing at (a) 700°C and (b) 900°C.
size $D$ is divided by average grain size $\bar{D}$. As found in Fig. 9, grain size distribution of the sample annealed at 900°C is narrower than that annealed at 700°C. There are a few (2.7%) relatively large grains over 2.5 times of average size in the sample annealed at 700°C, on the other hand such a relatively large grain is not found in the sample annealed at 900°C. Variety of the grain size distribution may come from the stored energy difference in cold rolled texture. At low recrystallization annealing temperature, $\gamma$-fiber grain with high stored energy nucleated early and $\alpha$-fiber grain with low stored energy nucleated slowly. 

4. Discussion

4.1. GBCD Analysis Based on Proposed Models for Secondary Recrystallization

It was already confirmed by investigations of May and Turnbull on high purity silicon steel that no secondary recrystallization occurred where inhibitors were absent. In our present experiment, contrary to common belief, onset of secondary recrystallization of the Goss texture was observed in high purity material.

First, aspects in terms of GBCD were investigated on primary recrystallization texture in which secondary recrystallization occurred. There are mainly three prevailing models concerning the Goss texture development during secondary recrystallization. The CSL (Coincident Site Lattice) grain boundary theory of different types $\Sigma 5$, $\Sigma 7$, and $\Sigma 9$ boundary is assumed to have high mobility. The Goss grains in primarily recrystallized sheets frequently meet matrix grains with such the CSL boundaries of high mobility, which will lead to the preferred growth of the Goss grains. Originally high mobility of the CSL boundaries was expressed in the presence of small amount of solute element in pure materials. The CSL boundaries have less solute atoms on it because of ordered structure. Afterward in terms of the CSL model, it is insisted that pinning force by inhibitors is smaller because of low energy of the CSL boundaries and this is supposed to be responsible for high mobility.

We proposed a different growth model based on the physical properties of the High Energy (HE) boundaries. The HE boundaries were defined as the boundaries with misorientation angles between 20° and 45° based on the experimental data by Dunn. From the analysis of primary recrystallization texture, frequency of the HE boundaries is proved to be the highest around the grains with the Goss orientation. The HE boundaries have more structural defects, which are linked to a high mobility and a high grain boundary diffusion rate. Quicker coarsening of inhibitors enables the HE boundaries to move earlier than other boundaries during final annealing. Thus, the grain having the Goss orientation has a growth advantage of having the highest number of mobile boundaries during secondary recrystallization. Prior to our work, Titorov and Gubernatorov had already proposed similar models based on high mobility of boundaries with misorientation 20° – 45° for the development of the Goss texture. It is to be noted that some of CSL boundaries such as $\Sigma 5$, $\Sigma 7$ and $\Sigma 9$ boundary are included in HE boundary because the misorientation angle falls between 20° and 45°. However the interpretation of the high mobility is quite different. CSL model assumes because of the low boundary energy and on the other hand, HE model assumes because of the high boundary energy.

In addition, a recently proposed Solid State Wetting (SSW) theory stresses the importance of low energy boundaries such as subboundary ($\Sigma 1$) and twin boundary ($\Sigma 3$). These types of low energy boundaries will extrude at triple junction of primarily recrystallized grains by wetting into the high angle grain boundary and separating two normal grains, thus leading to the growth of the Goss grains.

Based on the CSL model, using ODF of primary recrystallization texture of specimen annealed at 900°C the total frequency of the CSL boundaries $\Sigma 5$, $\Sigma 7$ and $\Sigma 9$ boundaries were investigated using Brandon criterion with various orientations. The calculated result in Euler space $\Phi 2=45°$ is given in Fig. 10. The grain with the Goss orientation has rather high frequency of the CSL boundaries (4.7%), however it is not the highest. The orientation having the highest frequency (6.7%) is $\{110\}<113>$ orientation which is rotated by 20 degree from ideal Goss orientation. Therefore to explain...
why Goss grain grows selectively needs more reasons.

Based on the HE model, using ODF of primary recrystallization texture of samples annealed at 900°C frequency of grain boundaries with a misorientation angle between 20 and 45° was investigated for various orientations. Results in Euler space $\Phi_2=0°$ and $\Phi_2=45°$ are shown in Fig. 11. It is apparent that around Goss oriented grains, the frequency of the HE boundaries is the highest. This characteristic is common to HGO and CGO containing inhibitors in our previous work.$^{21}$

Based on the SSW model, using ODF of primary recrystallization texture of the sample annealed at 900°C, the total frequency of low energy boundaries namely $\Sigma 1$ and $\Sigma 3$ boundaries was investigated. The calculated result is shown in Fig. 12. $\gamma$-fiber grains have the highest frequency of low energy boundaries and therefore $\gamma$-fiber grains are expected to grow selectively based on the SSW theory. In the present experiment, textures after normal growth, which were demonstrated in Fig. 6, are the $\gamma$-fiber texture. Therefore, the SSW model seems applicable to normal grain growth.

By the analysis of GBCD above, only the HE model seems applicable to the present experiment when describing the onset of secondary recrystallization of Goss grain.

### 4.2. Effect of the Microstructure

As Dunn$^{31}$ suggested that in order to cause the secondary recrystallization, it is necessary to inhibit the normal grain growth of the matrix, and usually this is attained by the presence of inhibitors. It was observed in our present experiment that in the sample which showed the onset of the secondary recrystallization, normal grain growth was suppressed even if it did not contain inhibitor elements.

As demonstrated in Fig. 9, grain size distribution of the primary recrystallized sample which led to secondary recrystallization is narrow, and this is considered to be helpful for the stabilization of matrix grains because the driving force for the normal grain growth comes from the difference in grain sizes between neighboring grains.

On the other hand, the sample directly given the final annealing after cold rolling without recrystallization annealing and that with low temperature primary recrystallization annealing showed normal grain growth and eventually failed to obtain secondary recrystallization. As already shown in Fig. 8, colonies of small grains is recognized in the sample annealed at 700°C. Such a clustering widens the grain size distribution. In the sample annealed at 700°C, there are a few (2.7%) relatively large grains over 2.5 times of average size. As found in Fig. 6, Goss orientation is a minor texture component, therefore the probability of relatively large grains having orientations other than Goss, and this may happen in the sample directly given the final annealing after cold rolling without recrystallization annealing and that with low temperature primary recrystallization annealing.

Also the sample annealed at high temperature (1050°C)
did not show secondary recrystallization. After isothermal annealing, samples in which secondary recrystallization did not occur have large grain size over 55 μm and this value is larger than 37.8 μm for the sample in which secondary recrystallization was successfully obtained. As Dunn\(^{31}\) suggested the driving force for secondary recrystallization is boundary energy of matrix grains which are eaten by secondary recrystallized grains. The magnitude of driving force is proportional to the reciprocal of the grain size of the matrix. Thus it is supposed that samples which did not show secondary recrystallization lost enough driving force for secondary recrystallization.

### 4.3. Effect of the Accumulation of the Primary Recrystallization Texture

In our previous work\(^{21}\) textures of HGO and CGO both containing inhibitors were investigated. The investigated ODFs of primary recrystallization are reproduced in Fig. 13. Compared textures of HGO and CGO in Fig. 13 with the ODF of the present experiment of primary recrystallization annealing temperature 900°C in Fig. 6, accumulation of texture in high purity material in the present experiment is rather strong.

The maximum intensity of ODF of HGO is 12, that of CGO is 8 and that of the present experiment of primary recrystallization annealing temperature 900°C is 16.

In the production process of HGO and CGO, soaking temperature before the hot rolling was above 1400°C for complete solid solution of inhibitor elements. Grain size before hot rolling was huge because of high temperature soaking. In order to suppress the evolution of band structure with \{100\}<011> orientation, which is harmful for the secondary recrystallization, carbon was added to HGO(0.07%) and CGO(0.04%) for partial γ-phase transformation during hot rolling. For the high purity material in the present experiment, the soaking temperature before the hot rolling was low (1100°C). Therefore grain size before hot rolling and also grain size after hot band annealing was small compared with HGO and CGO. After the cold rolling for HGO and CGO, coarse cementite particles originated from γ-phase were considered as nucleation sites of the recrystallization of random orientation. Reducing the carbon content to 10 ppm in high purity material, γ-phase transformation was completely suppressed so that coarse cementite particles considered as nucleation sites of the recrystallization of random orientation were not formed. Due to above mentioned effect of soaking temperature before the hot rolling and carbon content, strong
γ-fiber texture is considered to be realized. Strong accumulation of γ-fiber texture is also advantageous for the suppression of normal grain growth due to so-called texture inhibition, because of the low mobility of low angle boundary and twin boundary formed between γ-fiber grains.

The frequencies of the HE boundary in HGO and CGO in our previous work are shown in Fig. 14. It is apparent from Fig. 14(a), around grains with Goss orientation, the frequency of the HE boundaries is the highest in HGO. In Fig. 14(b), in CGO, the orientation having the highest frequency (70.1%) is {110}\langle1\bar{1}3\rangle orientation which is rotated by 20 degree from ideal Goss orientation. The Goss orientation has nearly the highest frequency (69.2%) in CGO.

In Fig. 15, comparison of the frequency of the HE boundaries around the Goss grain is given. Because of strongly accumulated γ-fiber texture, the frequency of the HE boundaries around the Goss grain in high purity material is higher than HGO and CGO. In terms of the HE model, growth advantage is the highest for the high purity material. However, as already shown in Fig. 5, the deviation angles from ideal Goss orientation of the high purity material are larger than those in HGO but comparable to CGO. Compared with HGO, the lack of inhibitors in the high purity material is considered to reduce the mobility advantage of HE boundaries and hence leads to larger deviation angle than HGO. Compared with CGO, higher frequency of HE boundary for Goss grain due to the strong texture in the high purity material may compensate the disadvantage caused by the lack of inhibitors.

Final cold-rolling reduction rate of high purity material in the present experiment is 86.5%, that of HGO is 85.3% and that of CGO is 55.0%. Heavy final cold-rolling reduction is also an important factor to obtain strong textures. In this point, previous work by May and Turnbull in which secondary recrystallization did not occur in high purity material was different. The final cold rolling reduction of their work was 50.0%, therefore accumulation of matrix texture seemed to be insufficient to obtain secondary recrystallization.

The frequency of HE boundaries around Goss grain was calculated from ODFs of primary recrystallized samples and the result is shown in Fig. 16. The frequency of HE boundaries around Goss grain rises as the recrystallization annealing temperature rises because of the enhancement of γ-fiber texture. It is considered that the increase in the frequency of HE boundaries is advantageous for the onset of secondary recrystallization. On the other hand, the increase in the grain size of recrystallized grains is disadvantageous for the onset of secondary recrystallization because of the reduction of the driving force. It is considered that the balancing effect of the frequency of HE boundaries around Goss grain and the grain size of recrystallized grains, only the sample with recrystallization annealing temperature at 900°C may lead to the onset of the secondary recrystallization.

### 4.4. Grain Boundary Mobility in High Purity Steel

The original idea of the HE model is that the high diffusivity of the HE boundaries leads to quick coarsening of precipitates during annealing. The resulting large particles have a lower pinning force on the moving boundaries than the smaller particles have on other boundaries. Goss grains have been reported to be surrounded by a higher fraction of these high mobility grain boundaries than grains with other orientations. However in the present experiment, the material is high purity without inhibitors or solute atoms other than Si and Mn. Therefore the growth model should be considered in the absence of inhibitors.

The CSL model originally was effective under the presence of a small amount of solute atoms due to less segregation toward the CSL boundaries. Then it was modified to experience weaker pinning force because of lower energy of the CSL boundary. Nakashima et al. suggested high mobility of $\Sigma 9$ boundary under the presence of solute Si. It may happen in the present experiment solute Si may enhance the mobility of the CSL boundaries. However as already shown in the present experiment, the Goss grain does not have the highest frequency of the CSL boundaries; application of the CSL model to the present experiment is questionable.

In the SSW model, the role of inhibitors or solute atoms has not yet been discussed so contribution of them is not clear. The assumption of this model may be applicable to normal grain growth in which inhibitors do not have a decisive role.

The relation between grain boundary energy and grain boundary mobility was discussed in our recent paper. It was shown that the grain boundary energy related to the grain boundary diffusion in Eqs. (1) and (2) by Borisov and this was validated by Pelleg.
\[
E = \left( \frac{kT}{a\alpha^2} \right) \ln \left[ \frac{\delta \theta}{a\alpha^2} \right] - \ln \left( m \right) \quad \cdots \cdots \cdots (1)
\]

\[
\theta = \frac{D_{gb}}{D_t} \quad \cdots \cdots \cdots (2)
\]

In Eq. (1), \( T \) is the absolute temperature, \( k \) is the Boltzmann constant, \( E \) is the grain boundary energy, \( m \) is the number of the atomic layer that forms a boundary, \( a \) is the lattice constant and \( \delta = ma \) is the grain boundary width.

In Eq. (2), \( \theta \) is the ratio of diffusion coefficients, \( D_{gb} \) is the grain boundary diffusion coefficient and \( D_t \) is the lattice diffusion coefficient.

It is expected from Eqs. (1) and (2) that the HE boundary has a high grain boundary diffusion coefficient.

The grain boundary mobility (\( M \)) is shown to be proportional as given by Sandstrom\(^{35} \) in Eq. (3).

\[
M = \delta D_{gb} b / kT \quad \cdots \cdots \cdots (3)
\]

In Eq. (3), \( \delta \) is the grain boundary width, \( D_{gb} \) is the grain boundary diffusion coefficient, \( b \) is the Burgers vector, \( k \) is the Boltzmann constant and \( T \) is the absolute temperature.

Combining these Eqs. (1) to (3), high grain boundary energy can be related to a high mobility through high grain boundary diffusion coefficient. Therefore the high mobility of the HE boundary can be achieved in high purity material without containing inhibitor elements. In our recent work,\(^{35} \) the dependence of grain boundary mobility on misorientation angle was calculated using Eqs. (1) to (3). It was shown that the HE boundaries have several times higher mobility than low angle (<15°) or very high angle (>45°) boundaries.

If the solute element such as S and P are included, solute atoms are preferably segregated to HE boundaries due to disordered structure and the grain boundary energy is considered to be reduced. According to the Eqs. (1) to (3), the difference in mobility can be reduced.

Therefore, it is considered that the reduction of impurity elements as low as possible exerts the inherent high mobility of the HE boundary. In conclusion, under the stability of the matrix grains realized by the narrow grain size distribution and by the strong texture inhibition, secondary recrystallization of Goss grains successfully attained due to the inherent high mobility of the HE boundary in high purity material.

5. Conclusions

(1) Onset of secondary recrystallization was observed in high purity material which did not contain inhibitor elements and the orientation of the secondary recrystallization was the Goss orientation.

(2) Normal grain growth was suppressed in the sample in which secondary recrystallization occurred during the final annealing. Narrow grain size distribution and strong texture accumulation were considered to inhibit the normal grain growth of the matrix grain.

(3) GBCD analysis on primary recrystallization textures were done based on the CSL, the HE and the SSW models. The HE model was applicable to secondary recrystallization and the SSW model was applicable to normal grain growth.

(4) The HE boundary theoretically was related to high mobility through high grain boundary diffusion coefficient. It was considered that reducing impurity elements exerted the inherent high mobility of HE boundary and hence led to the onset of the secondary recrystallization under the stability of the matrix grains realized by the narrow grain size distribution and by the strong texture inhibition.

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