Effect of hot band annealing on texture and grain size distribution of primary recrystallization in grain-oriented silicon steel

K J Ko\textsuperscript{1,1} and J T Park\textsuperscript{1,2}

\textsuperscript{1}Steel Product Research Laboratories, POSCO, Pohang, 37859, Korea.
\textsuperscript{1}kjko04@posco.com, \textsuperscript{2}jtpark20@posco.com

Abstract. During final high-temperature annealing in grain-oriented silicon steel, a few Goss grains grow exclusively fast and consume the matrix grains, which are related to the quality of the final product. The optimization of texture and microstructure in primary recrystallization is crucial to achieve the sharp Goss texture in grain-oriented silicon steel. The driving force for this phenomenon is the reduction of grain boundary area, which can be described as a reduction in grain boundary energy. The distribution of grain boundary and its energy determined by texture and microstructure of primary recrystallization are very important data to understand the optimization point. The hot band annealing is known to be a prerequisite for the high quality product in grain-oriented silicon steel. It can affect the evolution of microstructure and texture in primary recrystallization. In this study, the influence of the hot band annealing temperature on the texture and grain size distribution in primary recrystallization was investigated in detail.

1. Introduction

The grain size and texture after primary recrystallization annealing are very important for controlling the good magnetic properties in grain-oriented silicon steel. The uniform grain size distribution of primary recrystallization is considered to be helpful to improve the quality of final product in silicon steel [1]. The average grain size and distribution of grain size in grain-oriented silicon steel is determined by recrystallization and grain growth during primary recrystallization annealing process. The driving force for grain growth is the reduction of grain boundary area, and thus the total energy of the system is lowered. The driving force for the grain growth comes from the difference in grain sizes between neighboring grains. Thus, as growth occurs with rising temperatures the number of grains decreases as larger grains consume smaller grains. As smaller grains begin to shrink, their area diminishes and total energy is lowered. As grains are continually growing and shrinking over time, the mean grain size increases with forming a certain grain size distribution.

Hot band annealing is an important process to improve the magnetic properties of the product by modifying the microstructure, texture and precipitate distribution of the hot rolled sheet. It is well known that hot band annealing plays an important role to improve the inhomogeneity of the hot rolled sheet. Because the grain growth can be inhibited in the presence of fine precipitates which pin grain boundaries in place, the fine precipitations and their distribution should be considered for controlling the distribution of grain size during grain growth. The uniformity of grain size distribution is also an important factor to control the Goss texture in silicon steel[1,2]. In grain growth, the grain size distribution of the sample was significantly influenced by the temperature of hot band annealing.
In this study, the effects of the hot band annealing temperature on the texture and microstructure changes during primary recrystallization annealing were investigated.

2. Experimental procedure

The starting materials in this study were the 2.3mm-thick hot-rolled sample of Fe-3%Si, which employed AlN as an inhibitor to produce the grain-oriented (GO) electrical steel. The specimens were heated to high temperature to dissolve the fine precipitations which has non-uniform distribution, which is called hot band annealing process. The hot rolled sample were heated at 1000 ~ 1100℃, cooling to 850 ~ 950℃ by furnace cooling, holding for 2 min, and air-cooling below 800℃ and quenching in boiling water. Following the hot band annealing, the samples were cold rolled corresponding to approximately 89% thickness reduction using a laboratory mill. The cold-rolled samples underwent the primary recrystallization at 810 ~ 830℃ for 2 min in a wet hydrogen atmosphere for decaburization and recrystallization with grain growth.

For a sample analysis, the TD (transverse direction) cross sections of sample sheets were prepared by micro-polishing. Microstructure and orientations of the primary recrystallized samples were investigated by electron backscattered diffraction (EBSD), attached to a field emission scanning electron microscopy (FE-SEM, JEOL JSM - 6500F). The data related to microstructure and texture were obtained and analyzed using the orientation imaging microscopy (OIM 8) software packages. 220 × 3000μm² area scans with 1μm step size were used, enough to measure the microstructure with an average grain size of the samples in this paper. In order to calculate grain size from EBSD scan data, the grain boundaries were defined within the 5 degree tolerance angle and edge grains were excluded for the grain size calculation. About 300 ~ 500 points per a grain were used, if calculated from the average grain size in the analysis area.

3. Results and discussion

3.1 Microstructure and texture of primary recrystallized samples

Figure 1 illustrates EBSD data including an orientation map with image quality map. The EBSD data shows the microstructure after primary recrystallization annealing at 810℃, 820℃, and 830℃. The microstructure is showing that grain growth occurs and the decaburization and recrystallization were already finished due to 89% cold rolling process and high soaking temperature to recrystallization. The average grain size of samples is increased from 16 to 22μm with increasing the annealing temperature. As can be seen in the microstructure of figure 2, the frequency of fine size grain is decreased with increasing soaking temperature.

![Figure 1. IPF maps(TD) of samples annealed at (a) 810℃ (b) 820℃ (c) 830℃ for 2min.](image-url)

In order to compare the area fraction of grains by size, the grain size distribution for samples after primary recrystallization annealing at 810℃, 820℃, and 830℃ is shown in figure 2. As can be seen in figure 2, the grain size distribution shifted to right with increasing the annealing temperature. As the the soaking temperature increases, the area fraction of smaller grains than 25μm was decreased and the one of larger grains than 30μm was increased. As the the soaking temperature increases from 810℃ to 830℃, the area fraction of smaller grains than 25μm is reduced by 48.7%, 40.2% and 29.4%. On the other hand, the area fraction of larger grains than 40μm is increased by 10.9%, 17.9%, 25.7%. This
graph indicates that the large grains grow while consuming smaller-sized grains at the temperature of 820, 830 °C.

Figure 2. Grain size distribution of samples after primary recrystallization annealing at (a) 810 °C, (b) 820 °C, and (c) 830 °C.

Figure 3(a)~(c) shows the texture of samples after primary recrystallization annealing at 810 °C, 820 °C, and 830 °C, respectively. The primary recrystallization texture was developed similar after annealing due to 89% cold rolling process. All of the ODFs in figure 3(a) ~ (c) have the strong {111}<112> or {554}<225> components, and {411}<148> and {100}<012> components. The maximum intensity at these components in each sample was between 5 to 7. The Goss component, {110}<001> was not shown in ODFs because the volume fraction of Goss components in primary recrystallized samples was too minor. Calculated from EBSD scan data, the area fraction of Goss components in each sample was between 0 to 1.5%. As the maximum intensity of main texture components increased, the Goss components decreased. It should be noted that the EBSD scan area for each sample includes 1,300 to 2,600 grains. The number of grains in EBSD scan area depends on the size of the average grain. It was still small number of grains to acquire quantitative texture data [3]. The texture data from TD section showed some deviation from the measured position and the Goss component was too small to acquire reliable data.

Figure 3. ODFs represented in Phi=45 degree sections (intensity levels: 1, 1.5, 2, 2.5….) of samples after primary recrystallization annealing at (a) 810 °C, (b) 820 °C, and (c) 830 °C.

3.2 Microstructure and texture of primary recrystallized samples with different hot band annealing temperature

In order to compare the effects of the hot band annealing temperature on the grain size after primary recrystallization, the average grain size of primary recrystallized samples is shown in figure 4. As shown in figure 4, the average grain size of two samples were similar at 810 °C. Meanwhile, as temperature rose up to 830 °C, the grains of sample with hot band annealing at 1000 °C grew faster than the sample with hot band annealing at 1100 °C. In other words, there was the retardation of grain growth.
growth in the sample with hot band annealing at 1100°C. This retardation seemed to have resulted from the inhibition of grain growth by fine AlN precipitate formed during hot band annealing process.

In order to compare the area fraction of grains by size, the grain size distribution for samples with hot band annealing at 1000 and 1100°C were shown in figure 2. As can be seen in figure 5(b), in the case of hot band annealing at 1100°C, the grain size distribution of samples annealed at 810 and 820°C remained unchanged. Even when the annealing temperature was raised from 810°C to 820°C, small size of grains less than 20µm remained unconsumed by larger grains. So, the large grains did not grow further and the grain size of samples remained same as around 17µm after annealing at 820°C. As the annealing temperature rose up to 830°C, the grains of sample with hot band annealing at 1100°C began to grow late. In contrast, as shown in figure 5(a), the distribution of grain size in samples was shifted sequentially to the right at 810, 820, and 830°C for hot band annealing at 1000°C. As the annealing temperature rose up to 830°C, in particular, the grain size distribution has broadened. And also, by consuming small grains less than 25µm, the area fraction of grains over 50µm was increased considerably in figure 5(a). As the annealing temperature rose up from 810°C to 830°C, the area percentage of small size grains (less than 25µm) was reduced from 49% to 32% in figure 5(a). At the same time, the area percentage of large size grains (over 40µm) was increased from 11% to 24%. In the sample with hot band annealing at 1000°C, the area percentage of small size grains (less than 25µm) was reduced from 49% to 40%. At the same time, the area percentage of large size grains (over 40µm) was increased from 11% to 20%.

Figure 4. Grain size of primary recrystallized samples with hot band annealing at 1000°C and 1100°C

In the grain growth, the main difference between the two samples is whether or not the shrinkage of small size grains is inhibited at same temperature annealing. The differences in the inhibition of grain growth could be explained by differences in the precipitates size or volume fraction. [4] There was no difference in the volume fraction of precipitates between two samples, so the sample with hot band annealing at 1100°C might have finer precipitates. Generally, fine precipitates can dissolve at lower temperature than coarse precipitates due to Gibbs-thompson effect. Therefore, the grain coarsening temperature in steel depends on the size of AlN precipitates [5]. The finer precipitates may have a pinning effect and they could dissolve and lose their pinning force at lower temperature than the other coarser precipitates. As can be seen in figure 4 and 5(b), the fine precipitates in the sample with hot band annealing at 1100°C seems to dissolve and lose their pinning force to preserve the small grains during annealing at 830°C. On the other hands, the sample with hot band annealing at 1000°C seems
not to have the pinning force to preserve the small grains due to the lack of fine precipitates during primary recrystallization annealing. The difference in size of precipitates between two samples can be explained as follows. Higher temperature during hot band annealing the fine precipitates in the hot-rolled sample can dissolve more at higher temperature and they formed fine precipitates again during further annealing process. The higher temperature of hot band annealing can form higher density of fine precipitates. Therefore the sample with hot band annealing at 1100°C could have finer precipitates than the sample with hot band annealing at 1000°C.

![Figure 5. Grain size distribution of samples with hot band annealing at (a) 1000°C and (b) 1100°C.](image)

![Figure 6. ODFs represented in Phi=45degree (intensity levels: 1, 1.5, 2, 2.5…) primary recrystallized samples at (a, d) 810°C, (b, e) 820°C, (c, f) 830°C with hot band annealing at (a,b,c) 1000°C and (d,e,f) 1100°C.](image)

The primary recrystallization texture should be considered to control the Goss texture in grain-oriented silicon steel product [6-8]. Figure 6 shows the texture of samples after primary recrystallization annealing at 810°C, 820°C, and 830°C, respectively. All of the ODFs in figure 6 have the strong \{111\}<112> or \{554\}<225> components, and \{411\}<148> and \{100\}<012> components. The Goss component, \{110\}<001> was not shown in ODFs because the volume fraction of Goss components in primary recrystallized samples was too minor. Calculated from EBSD scan data, the area fraction of Goss components in each sample was between 0 to 0.8%. The primary recrystallization texture between these samples were not changed due to same cold rolling process (89% thickness reduction ratio).

The temperature of hot band annealing did not have much effect on the primary recrystallization texture but it had a significant effect on the grain growth during the primary recrystallization annealing. In grain growth, the grain size distribution of the sample was significantly influenced by the fine precipitates which were formed after the high temperature of hot band annealing.
4. Summary

The influence of the hot band annealing temperature on the texture and grain size distribution in primary recrystallized samples was investigated in detail. The temperature of hot band annealing did not have much effect on the primary recrystallization texture but it had a significant effect on the grain growth during the primary recrystallization annealing. The grains of sample with hot band annealing at 1000°C grew faster than the sample with hot band annealing at 1100°C. In grain growth, the grain size distribution of the sample was significantly influenced by the fine precipitates which were formed after the high temperature of hot band annealing.

References

[1] Woo J S, Han C H and Hong B D 1998 Acta Mater. 46 4905
[2] Hayakawa Y 2017 Sci. Technol. Adv. Mater. 18 480
[3] Wright S I and Adams B L 1990 Metall. Mat. Trans. A, 38 1845
[4] Park C S, Na T W, Kang J K, Lee B J, Han C H and Hwang N M 2013 Phil. Mag. 93 4198
[5] Wilson F G and Gladman T 1998 Int. Mater. Rev. 33 221
[6] Lin P, Palumbo G, Harase J and Aust K T 1996 Acta Mater. 44 4677
[7] Rajmohan N, Szpunar J A and Hayakawa Y 1999 Acta Mater. 47 2999
[8] Ko K J, Rollett A D and Hwang N M 2010 Acta Mater. 58 4414