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Evolution of Goss Orientation during Heating with Different Heating Rates in Cold-Rolled Grain-Oriented Electrical Steel

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Abstract In this study, cold-rolled Fe-3.1%Si grain-oriented electrical steel was heat-treated for decarburization at 830℃ after primary recrystallization at 720℃. Two different heating rates - a rapid (150℃/s) and a typical (20℃/s) one - were used to observe the microstructure in dependence of the heating rate during primary recrystallization. After primary recrystallization, the fraction of Goss-oriented grains in the surface and middle layer was similar in the sample subject to a rapid heating rate. But in the sample heated by applying typical heating rate, the fraction of Goss grains in the outside layer was more than 1.5 times that in the inside layer. After decarburization, the fraction of Goss grains decreased in the two samples heat-treated with a rapid and a typical heating rate for primary recrystallization. Goss grains had a lower kernel average misorientation than {411}<148> and {111}<112> oriented grains after decarburization, which means that Goss grains with a low misorientation angle may grow abnormally during secondary recrystallization.

Keywords Electrical steel, Texture, Goss orientation, EBSD, OIM

1. Introduction

Grain-oriented electrical steel is investigated in order to decrease the core loss and to increase the magnetic flux density and magnetic permeability. For grain-oriented electrical steel, managing the addition of alloying elements and the manufacturing process, including heat treatment, is very important for the control of the magnetic anisotropy [1-5]. For improving the magnetic properties of grain-oriented electrical steel, it is essential that such a steel has a strong {110}<001> texture (Goss texture). Recently, the manufacturing of electrical steel with a strongly developed Goss texture controlled by the manufacturing processes such as hot rolling, annealing of hot-rolled plates, cold rolling, and primary and secondary recrystallization has been studied. In previous research studies [6], the number of distributed Goss grains was enhanced in strongly deformed shear bands of steel, analyzed by using image quality of electron backscattering diffraction (EBSD) patterns. This means that Goss grains of the middle layer are more strongly deformed than those of the surface layer. Investigating the influence of the heating rate, it was found that rapid heating can help the formation of Goss grains by means of recrystallization.

Many grains with {111}<112> orientation were formed at around 700℃ during primary recrystallization. As the temperature increases up to 900℃, besides the main orientation {111}<112>, grains with {411}<148> orientation additionally developed. As the heating temperature increased, the fraction of {111}<112> oriented grains decreased heat-treated specimens at 1000℃ have been reported to change their main orientation from {111}<112> to {411}<148> [7]. In this study, the behavior of Goss grains was investigated in recrystallized and decarburized specimens at different heating rates, with a focus on the interplay of {411}<148> and {111}<112> oriented grains.

To characterize the local misorientation, the kernel average misorientation (KAM) was analyzed by electron back-scattered diffraction (EBSD). KAM is the average misorientation between a measured point and all its neighbors that can represent the perfection of a crystallite. The behavior of Goss, {111}<112>, and {411}<148>-oriented grains was investigated on the basis of KAM.

2. Experimental Procedure

In this study, a primarily recrystallized and decarburized sheet of Fe-3.1%Si grain-oriented electrical steel with the chemical composition of 0.06% C, 0.1% Mn, and 0.02% P was investigated during the manufacturing process. The

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initial sheet had a thickness of 2.0 mm, and was cold rolled to 0.3 mm in thickness. For the primary recrystallization, continuous heating was conducted until 720 ℃ with different heating rates, either rapid heating with a rate of 150℃/s or conventional heating with a typical rate of 20℃/s, which are selected to base on previous research [6]. The recrystallized sheet was decarburized at 830℃. The observed microstructures were in accordance with the heating rate during primary recrystallization and decarburization.

EBSD and orientation image mapping (OIM) were used for identifying Goss, {411}<148>, and {111}<112>-oriented grains and the area fraction, the grain size, and the distribution of Goss-oriented grains was observed in dependence of the heating rate. OIM was carried out in the transverse direction (TD)-plane of the sheet using field emission scanning electron microscopy (FE-SEM, Hitachi S-4300 SE). In case of the primarily recrystallized and decarburized steel sheet, the step size was 0.5 μm and 3 μm, corresponding to a total measured area of 500 μm × 250 μm and 4100 μm × 280 μm respectively. Goss, {411}<148>, and {111}<112> orientations are represented by red, blue, and green in OIM, respectively.

3. Results and Discussion

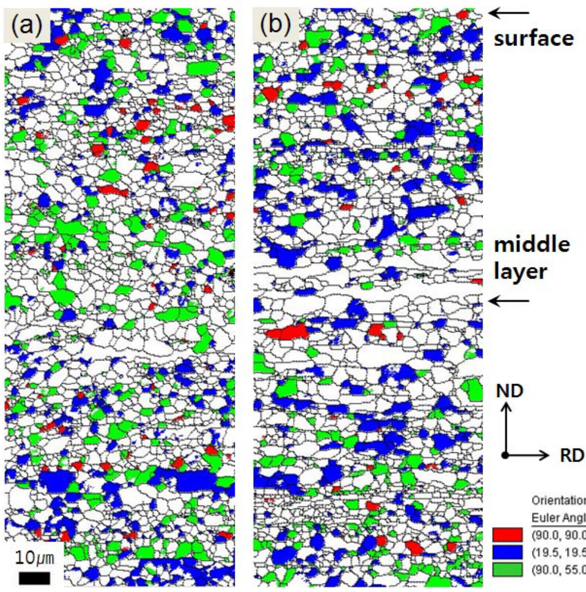

Figure 1. OIM of the recrystallized steel sheet obtained by EBSD with a step size of 0.5 μm in thickness, heated with (a) a rapid and (b) a typical heating rate, ND (normal direction)-RD (rolling direction) section

Figure 1 shows the resulting OIM of a part of the primary crystallized specimen with a step size of 0.5 μm. The tolerance angle was ±15° for a given orientation. Figure 2 shows the KAM distribution of Goss grains. The KAM was calculated considering with next-nearest neighbors. In case of rapid heating, the area fraction of Goss grains was 2.3% and the fraction of the surface and the middle layer was similar. However, in case of a typical heating rate, the result was different. The average area fraction of Goss grains was 1.85%, but the Goss fraction of the outside layer was 1.5 times larger than of in the inside layer. The average grain size of Goss oriented grains was 2.88 μm applying a typical heating rate and 2.51 μm for rapid heating. Hence, in case of rapid heating, the Goss fraction was larger and the grain size was smaller than for a typical heating rate. Figure 2(b) shows the KAM of all grains including Goss grains. KAM of the sample to typical heating rate was lower than in case of rapid heating. Therefore, specimens heat-treated with a typical heating rate showed almost perfect crystallites and formed bigger grains than rapidly heated samples. In other words, a rapid heating rate results in higher local stress compared to a typical heating rate.

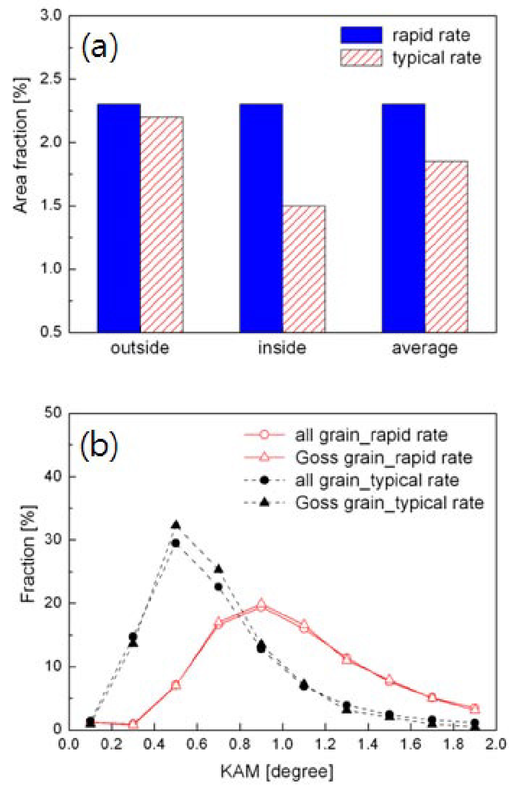

Figure 2. (a) Area fraction and (b) KAM distribution of Goss oriented grains after recrystallization, heated with a rapid and a typical rate

Figure 3 shows a part of the OIM of the decarburized specimen, measured with a step size of 3 μm, corresponding to a measured area of 4100 μm × 280 μm. Figure 4 shows the fraction of Goss grains and the distribution of KAM. In case of rapid heating, the average fraction of Goss grains is 1.95% and the grain size is 16.37 μm. In case of a typical heating rate, the average fraction of Goss grains is 1.3% with a grain size is 14.55 μm. After decarburization, the area fraction of Goss grains was decreased as compared with the sample after primary recrystallization. Comparing Figures 2(b) and 4(b), Goss-oriented grains with a low misorientation angle grew during decarburization at 830℃. This result could indicate that Goss grains grew with a KAM angle of less than 0.6° while those with a KAM angle of more than 0.6° disappeared during the decarburization process. Moreover, the sample heat-treated with a rapid heating rate has a smaller KAM angle after decarburization, simplying that rapid heating during recrystallization can support the generation of perfect Goss grains.

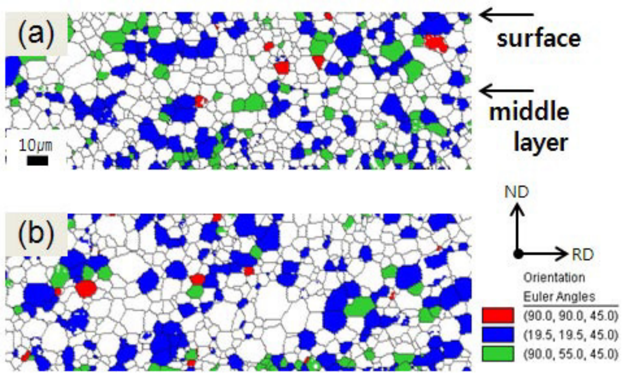

Figure 3. Orientation imaging mapping of decarburized steel sheet obtained by EBSD with a step size of 3 μm in thickness, heated with (a) rapid and (b) typical heating rate, ND-RD section

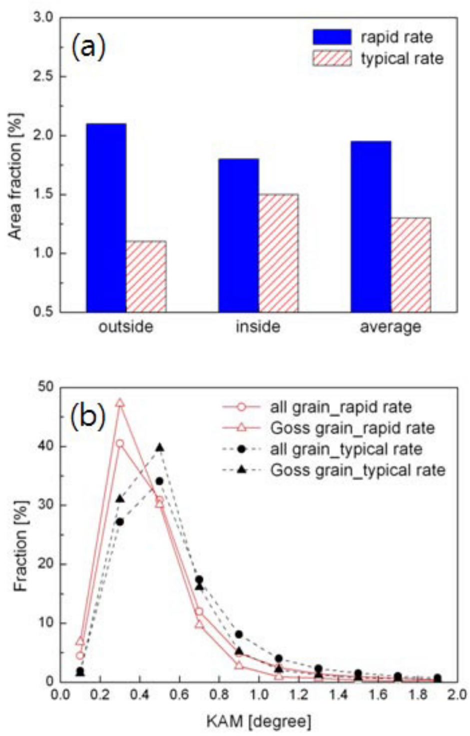

Figure 4. (a) Area fraction and (b) KAM distribution of Goss oriented grains after decarburization, heated with a rapid and a typical rate

The grain size after decarburization at 830℃ is grown by about 6.5 times in the sample subject to a rapid heating rate and about 5.1 times in case of a typical heating rate, which indicating that the heating rate during recrystallization affects the grain growth. The grain size as resulting frome primary recrystallization can change the onset temperature of secondary recrystallization and influences the magnetic properties after secondary recrystallization [8]. If the grain size increases, the driving force for grain growth decreases, which means the start temperature for secondary recrystallization increases. After secondary recrystallization is completed, the steel will have excellent magnetic properties [9].

The fraction of Goss grains decreased less in case of rapid heating than for a typical heating rate. The perfection of crystallites is reflected by a low KAM. Therefore, we expect that Goss grains disappear to a lesser extent compared with differently oriented grains during grain growth. These results can affect the abnormal grain growth during secondary recrystallization.

Figure 5 shows the area fractions of {411}<148> and {111}<112> oriented grains which can affect the growth of Goss grains. For the two different heating rates, after decarburization the {411}<148> orientation fraction is increased by about 1.5 times and the {111}<112> orientation fraction is decreased by about 0.8 times. The fractions of {411}<148> and {111}<112>-oriented grains, neighbored by Goss grains, are shown in Figure 6. This figure suggests a correlation between {411}<148>, {111}<112>, and Goss orientation. In case of rapid heating, the fraction of {411}<148>-oriented grains decreased by about 0.6 times after decarburization, but {111}<112> fraction is not changed. In case of a typical heating rate, the {411}<148> fraction decreased by about 0.7 times after decarburization, but, again, the fraction of the {111}<112> orientation is not changed.

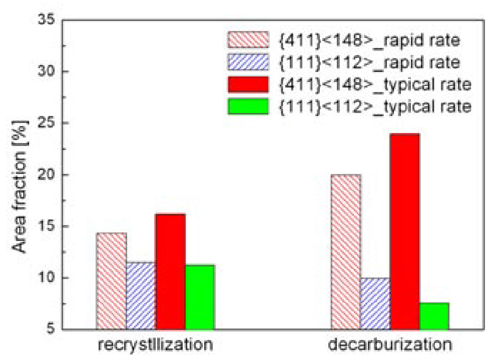

Figure 5. Area fraction of {411}<148> and {111}<112> oriented grains in the sheet sample after recrystallization with a rapid and a typical heating rate and after decarburization

After decarburization, the fraction of the Goss orientation is decreased, whereas the fraction of the {411}<148> orientation is increased. In addition, the number of grains of {411}<148> orientation neighbored by Goss grains is decreased. Therefore, we expect that the growth of {411}<148> grains encroached Goss grains. The fraction of {111}<112> grains is similar after primary recrystallization and decarburization. This result shows that {111}<112> grains have a weaker relationship to Goss grains in case the grain growth takes place at 830℃. In addition, the heating rate affected the neighboring distribution of Goss grains to a lesser extent.

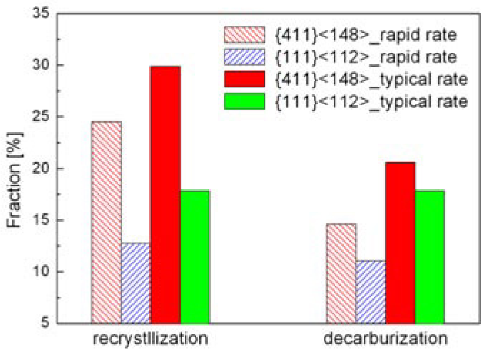

Figure 6. Fraction of {411}<148> and {111}<112> oriented grains which are neighbored with Goss grains after recrystallization with a rapid and a typical heating rate and after decarburization

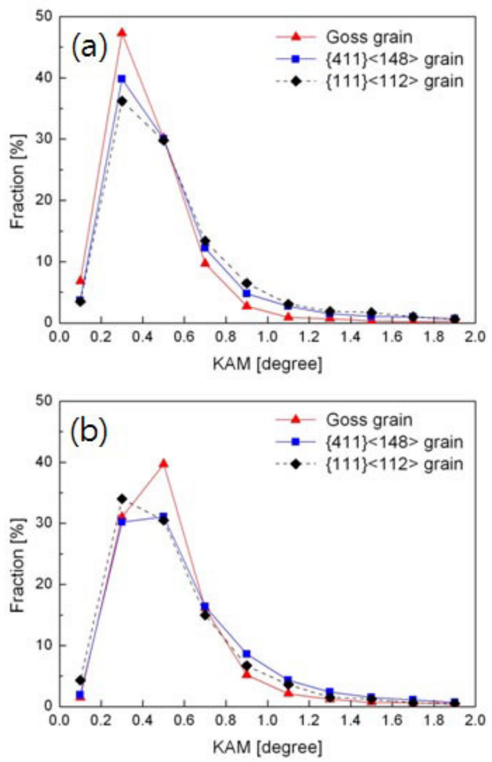

Figure 7. KAM distribution of Goss, {411}<148>, and {111}<112> oriented grains after decarburization, heat-treated with (a) a rapid and (b) a typical rate

Figure 7(a) and (b) shows the KAM distribution of Goss, {411}<148>, and {111}<112> oriented grains after decarburization at 830℃. In the rapidly heated sample, 77.4% of the Goss oriented grains have a KAM angle of less than 0.6°, and in the sample heat-treated with a typical heating rate, 70.7% of the Goss oriented grains have such a low KAM angle of less than 0.6°. In other words, the KAM of Goss grains was significantly smaller; accordingly, the crystallites are more perfect in case of a rapid heating rate than for a typical heating rate. The driving force for grain growth can be the difference of internal energy between strained and unstrained grains. The grains form as small grain and grow until they completely consume the parent grains, processes that involve short-range diffusion [10]. Considered from the perspective of KAM, Goss grains with a low KAM can grow easily because they have a low internal energy. The KAM of Goss grains is lower than that of {411}<148> and {111}<112>-oriented grains. It is expected that these {411}<148> and {111}<112> oriented grains can be consumed for the abnormal growth of Goss grains during secondary recrystallization. This trend strongly appears in case of rapid heating during recrystallization and, therefore, rapid heating is expected to be beneficial for the growth of Goss grains.

4. Conclusions

1. After primary recrystallization, the KAM of the sample heat-treated with a typical heating rate was lower than in case of rapid heating. Therefore, specimens heated by a typical rate showed almost perfect crystallites that were bigger in size than in case of a rapid heating rate. In other words, a rapid heating rate results in higher local stress compared to a typical heating rate.

2. After decarburization, the area fraction of Goss grains was reduced compared with the sample after primary recrystallization. Moreover, the sample heat-treated with a rapid heating rate has a smaller KAM angle after decarburization, implying that rapid heating during recrystallization can support the generation of perfect Goss grains.

3. The KAM of Goss grains is lower than that of {411}<148> and {111}<112> oriented grains. It is expected that these {411}<148> and {111}<112> oriented grains can be consumed for the abnormal growth of Goss grains during secondary recrystallization.

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