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Effect of magnetic field applied during secondary annealing on texture and grain size of silicon steel

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Abstract

Temper cold rolled silicon steel samples were annealed with and without an applied magnetic field. The final grain size was the same for both annealing conditions. Application of a magnetic field affected texture development by increasing the strength of the Goss component and decreasing the intensity of the gamma fiber.

Keywords: Soft magnet; Magnetic annealing; Texture; Grain growth

1. Introduction

Silicon steel is a soft magnetic material of prime importance in the electrical industry, which consumes hundreds of thousands of tons every year [1–3]. Grain non-oriented silicon steels (GNO) are commonly used in hydroelectric power plant generators and electric motors. The magnetic behaviour of this material is mainly controlled by two microstructural features: the final texture and the average grain size. Texture, or crystallographic preferred orientation, is produced as a consequence of grain boundary migration during recovery, recrystallization, and grain growth that is affected by anisotropy in energy, mobility and stored energy. It is believed that the preferred orientation is enhanced by the application of external fields and that the sample position with respect to applied magnetic field direction is significant. That this should be the case in ferromagnetic materials is reasonable in light of the pronounced magneto-crystalline anisotropy exhibited by ferromagnetic materials such as iron.

Magnetic fields have been shown to have a significant effect on texture and microstructure evolution in ferrous alloys [4]. It has been noticed that annealing in magnetic fields retards recrystallization and consequently develops a texture different from that formed in the ordinary recrystallization process [4–6]. Grain size has a great

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effect on magnetic losses [7–10], which directly affects the performance of electrical machines making the control of grain size to be an important issue when efficiency is required. When the grain size diameter d increases, the hysteresis loss decreases in proportion to $1/d$ whereas the eddy current loss increases in proportion to d. The total core loss is minimized at an optimum grain diameter in the range of 150 and 200 μm [11]. GNO steels are intended to exhibit uniform magnetic properties in all directions [2]. For many magnetic applications, however, the ideal final texture is the $\{1\,0\,0\}\langle uvw\rangle$ also known as $\{1\,0\,0\}$ fiber texture, where the grains have their $\{1\,0\,0\}$ planes parallel to the sheet surface and all possible rotational positions about this normal [1,11,12]. The so called Goss texture $\{1\,1\,0\}[1\,0\,0]$ is also a very attractive component of texture in magnetic materials since it has the highest permeability direction, $\langle 1\,0\,0\rangle$, parallel to the rolling direction and the $[1\,1\,0]$ direction, which is an intermediate permeability direction, parallel to the normal direction [3,11].

2. Experimental setup and procedure

The material used in this investigation was a GNO low silicon steel, 10% temper cold rolled and primarily annealed at 815 °C. The chemical composition of the sample is shown in Table 1. Coupon specimens $5 \times 8 \times 0.5$ mm were sampled from the sheet with the longitudinal axis parallel to the rolling direction. The samples were annealed in a magnetic field of 8 T. The highest available field strength was used in order to maximize its influence on texture development. The annealing temperatures were 737, 787 and 837 °C; the annealing time was 1 h and the atmosphere used was high purity argon. In order to evaluate the effect of the magnetic field, the temper cold rolled specimens were annealed at the same conditions (temperature, time and inert atmosphere) as for the magnetic annealing but without any magnetic field. Grain size was measured using an optical microscope. Texture was measured using a Philips X'Pert MPD equipment. Pole figures and ODFs were calculated using PC-Texture 3.0 and PopLA software.

Table 1
Chemical composition

Material	%Si	%C	%Mn	%P	%S	%N	%Al
Iron–silicon	0.28	0.008	0.57	0.013	0.014	0.003	0.06

3. Description of magnetic annealing

The magnetic annealing was carried out in a cylindrical furnace that was inserted into the 195 mm bore of the high field magnet. An alumina sample holder, containing the samples, was inserted inside the furnace and positioned at the center of the magnetic field. The samples were positioned perpendicular to the applied magnetic field. Positioning parallel to the applied field was not possible in this work due to a limitation in the sample holder apparatus. The effect of sample position relative to the magnetic field will be investigated further. The furnace was turned on and its temperature was raised up to the annealing temperature followed by ramping the magnetic field up to 8 T. The magnetic field strength and the temperature were kept constant during the annealing time. After that, both the furnace and the magnet were turned off and the samples cooled down slowly to room temperature inside the furnace. Table 2 shows the nomenclature of the samples according to the mode of annealing and annealing temperature.

Table 2
Identification of the samples according to their annealing mode and annealing temperature

Sample	History
AR	Before secondary annealing
M73	After magnetic annealing at 737 °C
M78	After magnetic annealing at 787 °C
M83	After magnetic annealing at 837 °C
O73	After ordinary annealing at 737 °C
O78	After ordinary annealing at 787 °C
O83	After ordinary annealing at 837 °C

4. Results and discussion

After magnetic annealing, the samples were prepared for grain size measurement and texture analysis. The average grain size of the samples after primary annealing was 150 μm. The grain size increased to 200 μm after secondary annealing regardless of whether a magnetic field was applied during secondary annealing. It has been shown previously [5,6] that a magnetic field applied during the annealing process retards recrystallization. Based on these findings for the same annealing temperature and annealing time, the final grain size of the samples annealed in the presence of a magnetic field might be expected to be smaller. Watanabe et al. [5], working at 2 and 5 T; and Xu et al. [6], working at 5 T, have shown a large difference in grain size between samples annealed with and without magnetic field. However, Matsuzaki et al. [13] working at 15 T; Masahashi et al. [4], working at 10 T; and results from this paper have shown that the final grain size of FeSi samples annealed with and without magnetic field were similar.

The difference in the results of final grain sizes could be related to the fact that although magnetic field retards recrystallization it can also provide a driving force for grain boundary motion [13]. For magnetic fields at the order of 5 T or less, one can see the difference in grain size after the primary annealing [5,6]. For higher magnetic fields (15, 10 and 8 T) [4,13], however, no difference in grain size after primary annealing was observed, suggesting that the retardation of nucleation during recrystallization was compensated by the driving force for boundary motion, given by the high magnetic field, leading to a very similar final average grain size after the two distinct annealing processes. For annealing at higher fields, the most remarkable difference between the two processes should therefore be the orientation of the recrystallized grains and the grain boundary character distribution [4,5,13,14].

Although secondary magnetic annealing did not affect grain growth, annealing in the presence of the 8 T magnetic field did influence texture development. From the results shown in Fig. 1, it appears that an external magnetic field enhances the growth of the Goss component below and just above the Curie temperature. In the paramagnetic state (67 °C above Curie temperature) the effect of the applied magnetic field on the growth of the Goss component is still apparent although ordinary annealing leads to higher intensities of this component. At 837 °C, i.e., above the Curie temperature, the magnetic field seems to be less effective than at temperatures below (737 °C) and just above (787 °C) the Curie point. Kim and Park [14] also found that the effectiveness of magnetic annealing was greater for annealing at temperatures close to the Curie point. Similar results were also found by Tsurekawa et al. [15] when sintering iron powder in the presence of a magnetic field.

It has been found that an applied magnetic field during annealing can play a significant role even when the material is in its paramagnetic state [5,15]. As mentioned by Tsurekawa et al. [15], a possible explanation for the magnetic effect observed above the Curie temperature is that the magnetic moments are forced to orient along the magnetic field direction by an external magnetic field against the thermal motion of the atoms which tends to

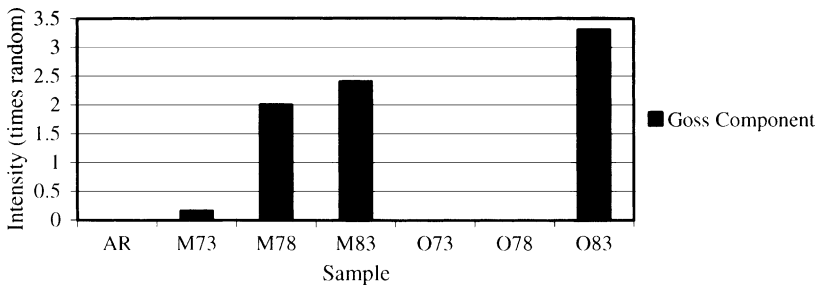

Fig. 1. Intensity of {1 1 0}⟨0 0 1⟩ (Goss component) after annealing with and without an applied magnetic field.

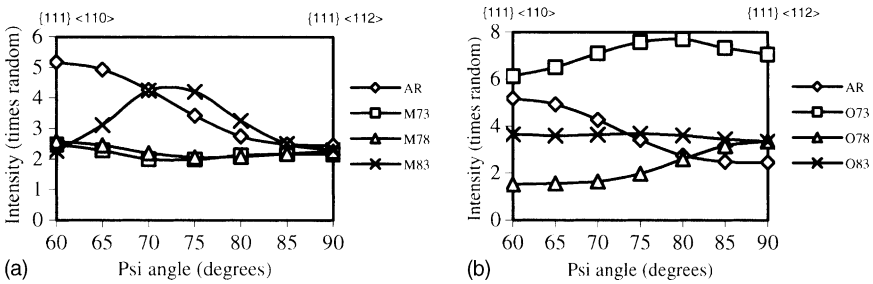

Fig. 2. Variation in intensity along the gamma fiber (a) after annealing in a magnetic field and, (b), after annealing without an applied magnetic field.

randomize the directions of any moments that may be aligned. The forced magnetic ordering together with the magneto-crystalline anisotropy may provide a driving force for selective grain growth even above the Curie temperature.

The gamma fiber, $\{1\,1\,1\}\langle uvw\rangle$, is detrimental for the magnetic properties of silicon steel, therefore the development of the gamma fiber was also examined. Fig. 2 shows the intensities on the gamma fiber after both magnetic and ordinary annealing. The results show that the gamma fiber decreased after magnetic annealing for both 737 and 787 °C and increased after ordinary annealing, especially for annealing at 737 °C.

$\{1\,1\,1\}$ Pole figures have also shown that magnetic annealing was more effective in decreasing the volume fraction of crystals with their $\{1\,1\,1\}$ planes parallel to the sheet surface, i.e. the gamma fiber, than annealing in the absence of a magnetic field. Fig. 3(a) and (b) show that the fraction of $\{1\,1\,1\}$ planes with their direction parallel to the rolling direction decreased after magnetic annealing, at 737 °C, from 3.61 times random to 2.05 times random. The same family of grains showed

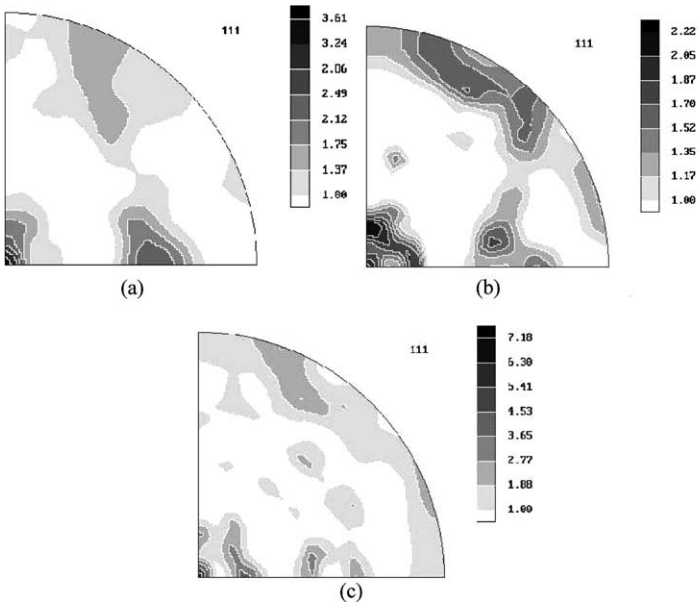

Fig. 3. $\{1\,1\,1\}$ Pole figure: (a) Before annealing, (b) after annealing at 737 °C in a magnetic field, (c) after annealing at 737 °C without an applied magnetic field.

an increase after ordinary annealing to 7.18 times random (Fig. 3(c)).

Annealing at higher temperatures of 787 and 837 °C showed little difference in texture development, based on analysis of the {1 1 1} pole figures with and without application of a magnetic field.

Magnetic annealing was found to enhance the selectivity {1 1 0}(0 0 1) component of texture and to suppress {1 1 1}-axis orientation in the secondary recrystallized microstructure. The effectiveness of magnetic field was more prominent in the condition of annealing temperature near to magnet transformation temperature. These results are in agreement with the analysis by Kim and Park [14].

5. Conclusion

Magnetic field applied during annealing had little effect on grain growth. It did, however affect texture development as follows:

1. The Goss component increased at the lowest annealing temperature (737 °C), and continued to increase as the annealing temperature increased, reaching 2.4 times random after annealing at 837 °C. For the annealing without a magnetic field, this texture component first appeared only at the highest annealing temperature.
2. The intensity of the gamma fiber decreased for annealing in the presence of a magnetic field, and consequently the intensity of grains {1 1 1} oriented parallel to the normal direction of the sheet. Annealing without magnetic field, however, increased the intensity of the gamma fiber.

Even in the paramagnetic state (837 °C), the magnetic field still affected texture development as evident from the intensification of the Goss component. This finding suggests that grain boundary migration in FeSi can be affected by magnetic field even above the Curie temperature, where spontaneous magnetization and magneto-crystalline anisotropy are no longer present.

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