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Iron Loss of Grain Size Controlled Very Thin Grain-Oriented Silicon Steels

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Abstract– **Very thin (less than 100 μm) grain-oriented silicon steels are known to have lower iron loss than iron-based amorphous materials. It is possible to reduce the iron loss of very thin grain-oriented silicon steels further by applying new magnetic domain refining techniques. One method for magnetic domain refining is to control the grain size. We observed the magnetic domains and measured the iron loss of very thin grain-oriented silicon steels that had various grain sizes. We controlled grain size in samples to be from 0.25 mm to 2.3 mm without changing B_8. This experiment shows that the magnetic domain width can be made narrower by decreasing the grain size, which reduces the eddy current losses. On the other hand, samples with larger grain size have lower Hc and lower hysteresis losses. Therefore there is an optimum grain size for the lowest iron loss of very thin grain-oriented silicon steels.**

Introduction

We have reported that very thin (less than 100μm) grain-oriented silicon steels with tertiary recrystallized [1] (110)[001] textures have excellent soft magnetic properties [2],[3]. Furthermore we made a report of the effect of the magnetic domain refining techniques for decreasing the iron loss, such as chemical etching techniques or applying tensile stress [4]. However, using these conventional techniques will complicate the manufacturing process.

In this work, we investigated the effect of the grain size on the magnetic domain width and the iron losses of very thin grain-oriented silicon steels. We observed the magnetic domains and measured the iron losses of very thin grain-oriented silicon steels with various grain sizes (0.25 mm–2.3 mm).

Experimental Procedure

We made 33 μm–35 μm thick grain-oriented silicon steels by cold-rolling and annealing conventional grain-oriented silicon steel of 270 μm thickness. Due to this annealing, tertiary recrystallization occurred. After the tertiary recrystallization was completed, the silicon steels had very sharp (110)[001] textures and had magnetic inductions at 800 A/m (B_8) of over 1.95 T.

The grain size was controlled by changing the cold-rolling speed and by changing annealing conditions [5] for the tertiary recrystallization. The magnetic domains were observed dynamically using a scanning electron microscope (SEM) [4]. The DC magnetic properties were measured by using a BH loop tracer. The iron losses were measured by a single sheet tester.

Results and Discussions

A. DC Magnetic Properties

At first we investigated the effect of grain size on the DC magnetic properties of very thin grain-oriented silicon steels. Figure 1 shows dependence of the magnetic induction at 800 A/m (B_8) and the coercive force (H_c) on the grain size. The magnetic induction at 800 A/m (B_8) was over 1.95 T in all samples independent of grain size. Only sharp (110)[001] grains existed as nuclei for tertiary recrystallization, because the grain-oriented silicon steel sheets we cold-rolled had sharp (110)[001] textures. Accordingly, no grains with [001] axis much deviant from the rolling direction appeared when the number of grains increased by decreasing the grain size. Therefore all samples had very high magnetic inductions independent of the grain size. On the other hand, this figure shows that the coercive force increased with decreasing grain size in samples having grain size less than 1 mm. The decrease of the grain size caused an increase of grain boundary area. Therefore the decrease of the grain size disturbed the movement of the magnetic domain walls, and made the coercive force larger.

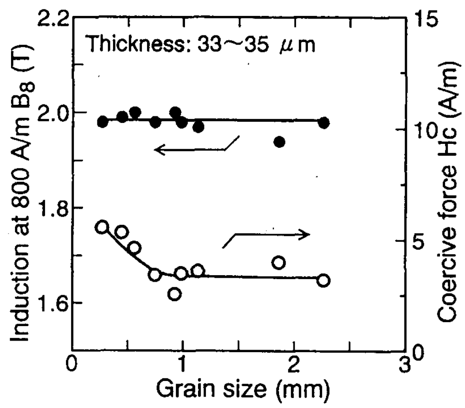

Fig. 1 Grain size dependence of the DC magnetic properties.

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B. Magnetic Domains

We observed the magnetic domains of the samples to clarify the effect of the grain size on the domain width. There are many studies on magnetic domain structures of grain-oriented silicon steels [6]-[10]. Generally, the 90° magnetic domain walls have close a connection with the iron loss of grain-oriented silicon steels [10]. However in very thin grain-oriented silicon steels, we never find any 90° magnetic domains [5]. These samples are very thin and have sharp [001] axis. Therefore they are composed of only 180° magnetic domains.

Figure 2 shows the grain size dependence of the number of magnetic domain walls. In this experiment the maximum magnetic induction was 1.3 T. When the magnetizing frequency was 50 Hz, the number of magnetic domain walls increased from 1.0 mm^{-1} to 1.75 mm^{-1}, while the grain size decreased from 2.3 mm to 0.25 mm. The increase of grain boundary area with the decrease of grain size raised the magnetostatic energy. Accordingly the number of magnetic domain walls increased.

To clarify the dependence of the magnetic domain wall number upon exciting frequency, we measured the number of magnetic domain walls at various exciting frequencies (N_d) in comparison with the number of magnetic domain walls in the demagnetized state (N_s). Figure 3 shows the magnetizing frequency dependence of the increase of the magnetic domain walls (N_d-N_s) of samples with grain size of 0.26 mm, 0.44 mm, and 0.74 mm. In the sample of 0.74 mm grain size the magnetic domain wall number increased with exciting frequency over 100 Hz. On the other hand, in the sample having a grain size of 0.44 mm, the magnetic domain wall number was constant at exciting frequencies less than 200 Hz. The number of magnetic domain walls of the sample of 0.26 mm grain size didn't increase under 400 Hz. However, at 800 Hz the increase of the number of magnetic domain walls was larger in samples having smaller grain size. This result indicated that decreasing the grain size was more effective for the magnetic domain refining at higher magnetizing frequencies.

The magnetic domain width will be narrower in very thin grain-oriented silicon steels having smaller grain size. At higher frequencies the number of magnetic domain walls will be easier to increase.

C. Iron Losses

It was clarified that decreasing grain size was very effective in refining the magnetic domains. Then we measured the iron losses, the eddy current losses, and the hysteresis losses at magnetizing frequencies up to 800 Hz to investigate the effect of refining the magnetic domains.

Figure 4 shows grain size dependence of the iron loss, the eddy current loss, and the hysteresis loss at magnetizing frequencies of 50 Hz (a) and 400 Hz (b). At both frequencies the hysteresis loss was raised by decreasing the grain size. It was caused by the increase of the grain boundary area in the same way as the increase of Hc. On the other hand, the eddy current loss decreased with decreasing the grain size. As shown in figure 2, decreasing the grain size increased the number of 180° magnetic domain walls. Therefore the eddy current loss decreased.

Figure 4 also shows that the iron loss, i. e. the sum of the hysteresis loss and the eddy current loss, had a minimum at one grain size. At 50 Hz, the lowest iron loss of 0.22 W/kg was obtained without additional domain refining techniques at a grain size of about 0.8 mm. At 400 Hz, almost all the iron losses were due to the eddy current losses. Therefore the optimum grain size became smaller than that at 50 Hz.

These experiments show there was an optimum grain size for each frequency. Figure 5 shows the optimum grain size as function of magnetizing frequencies (50 Hz-400 Hz). Clearly at higher frequencies the grain size yielding minimum iron loss will be smaller than at lower frequencies. At higher frequencies, the eddy current loss

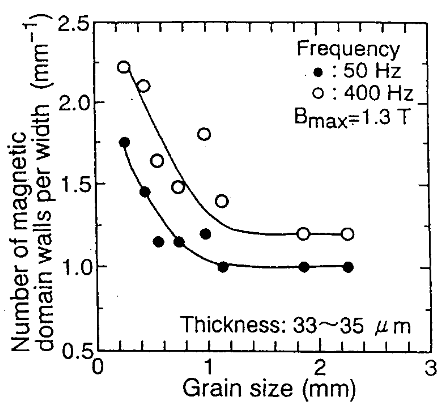


Fig. 2 Grain size dependence of the number of magnetic domain walls.

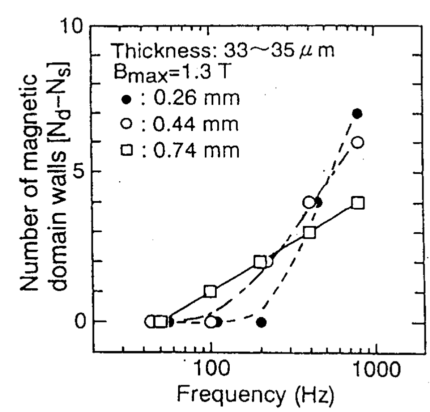
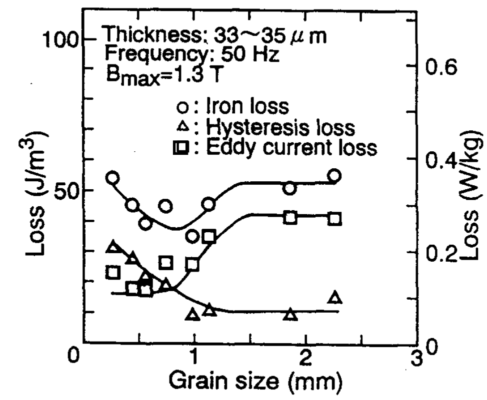


Fig. 3 Magnetizing frequency dependence of the increase of the magnetic domain walls.



(a) At 50Hz

(b) At 400 Hz

Fig. 4 Grain size dependence of losses.

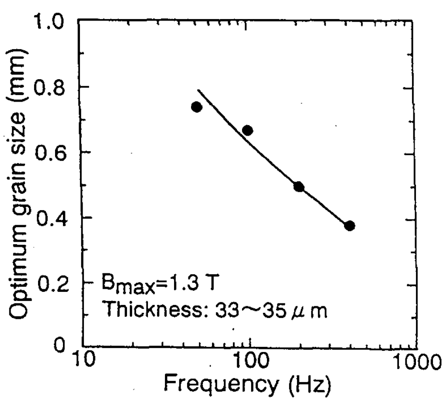


Fig. 5 Optimum grain size as function of magnetizing frequency.

accounts for the larger part of the iron loss. Hence, the decrease of the eddy current loss by magnetic domain refining will be more effective. Accordingly, the iron loss is lower the smaller the grain size.

Conclusion

We measured the DC magnetic properties, the magnetic domain width, and the iron loss of very thin grain-oriented silicon steels having various (0.25 mm–2.3 mm) grain sizes at magnetizing frequency up to 800 Hz. The major results were as follows:

(1) The magnetic induction at 800 A/m (B_8) of very thin grain-oriented silicon steel was independent of the grain size. The coercive force (H_c) increased with decreasing grain size less than 1 mm.

(2) The number of magnetic domain walls increased by decreasing the grain size. The number of magnetic domain walls was easier to increase at higher frequencies.

(3) The decrease of the grain size reduced the eddy current loss, and raised the hysteresis loss. Therefore there was an optimum grain size for each frequency.

(4) The lowest iron loss of $W_{13/50}$=0.22 W/kg was obtained without conventional magnetic domain refining techniques at the grain size of 0.8 mm.

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