Effect of Grain Size on Domain Structure of Thin Nonoriented Si–Fe Electrical Sheets

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***Abstract*—Domain configuration of the nonoriented Si–Fe electrical sheets with different grain size was observed decreasing their sheet thickness by using the Kerr effect. It was found that the nonoriented sheet needs multiple grains in the sheet thickness direction to eliminate the normal magnetization component in the flux closing structure causing excessive eddy current loss.**

***Index Terms*—Anomaly factor, domain structure, grain size, nonoriented Si-Fe electrical sheets.**

I. INTRODUCTION

ENERGY loss dissipated as heat in nonoriented electrical sheets costs \$1.7 trillion/yr in the world. So, the loss improvement of nonoriented Si–Fe sheets, even if it is small, is very important for the CO_2 problem. Recently, effort has been made to decrease the iron loss of nonoriented Si-Fe sheets by decreasing sheet thickness [1]–[3]. It is known that the anomaly factor tends to increase steeply when the sheet thickness is decreased less than 0.2 mm [3]. We reported that the magneto-static coupling between grains become loose and the magnetization component normal to the sheet plane increased when the sheet thickness is comparable to the grain size [4]. Such normal magnetization component is responsible for the increase in the eddy current loss, while the small grains give rise to the increase in hysteresis loss. So the optimization of the grain size relative to the sheet thickness is important. In the present work, we explored the effect of grain size on the domain structure of thin nonoriented Si-Fe sheets with different grain size.

II. EXPERIMENTAL PROCEDURE

The nonoriented 3% Si-Fe sheets (50A290 and 50A1300) provided by Nippon Steel Co. have rectangular dimensions of 50 × 3 mm and 40 mm × 4 mm rectangle, respectively. The specimens were mechanically polished and annealed in a vacuum of 1×10^{-3} Pa at 800 °C for 1 h to avoid the additional introduction of mechanical stress. The specimens were then thinned chemically from the thickness of 0.5 mm down to 0.06 mm from the underside as shown in Fig. 1. The averaged grain sizes of these two specimens are 0.2 mm (50A290) and 0.04 mm (50A1300), being bigger and smaller than the sheet thickness, respectively. Here, we let Si–Fe(L) and Si–Fe(S) stand for these two thinned Si-Fe sheets. A Kerr microscope was used to view magnetic domain structure. Orientation of the easy axis of individual small grain was evaluated by the electron back-scattered pattern (EBSP) to clarify the relation between the domain structure and the crystallization orientation.

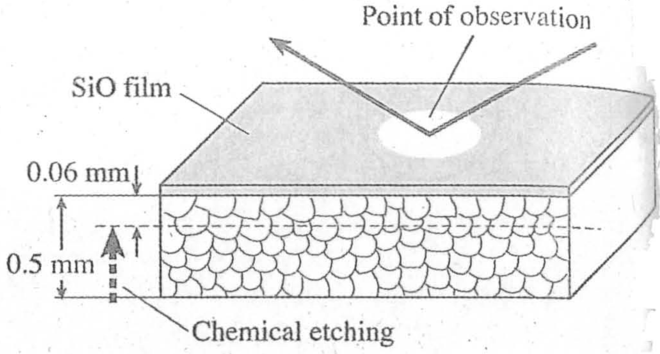

Fig. 1. Specimen for domain observation.

III. RESULTS

Fig. 2 shows magnetic domains and direction of the easy axis of individual grain of the thinned 0.06-mm-thick Si–Fe(L) specimen with averaged grain size of 0.2 mm. The domain picture was taken at the remanent state after application of a dc field of 8 kA/m in the rolling direction. The incidence of the polarizing light in a Kerr microscope is along the rolling direction, so the dark and bright domains in Fig. 2(a) have magnetization pointing in upward and downward directions, respectively. In Fig. 2(b), the easy axis of cubic anisotropy distributing within an angle of 35.2° which represents the angle between ⟨100⟩ direction and (111) plane was picked up and shown by an arrow with the tilting angle from the sheet surface (so-called β-angle). The solid arrow indicates the easy axis direction nearest to the sheet surface. On the other hand, we show the direction next near the surface at the broken arrow if β-angle is less than 20°. According to the number of arrows and the β-angle, we classified the crystallographic orientation of the individual grain into near (100), (110) and (111) planes. It is estimated that grains with two arrows have surfaces close to (100) plane. We set a tentative boundary for the β-angle between near (110) and (111) plane as 20°. This classification is shown in Fig. 2(b) by changing the tone of the grain surface. It is seen that grains with near (100) plane and their adjacent grains near (110) plane tend to exhibit stripe domain configuration running in the direction transverse to the rolling direction. The stripe domain configuration would reflect the closure domain structure underneath the surface. It

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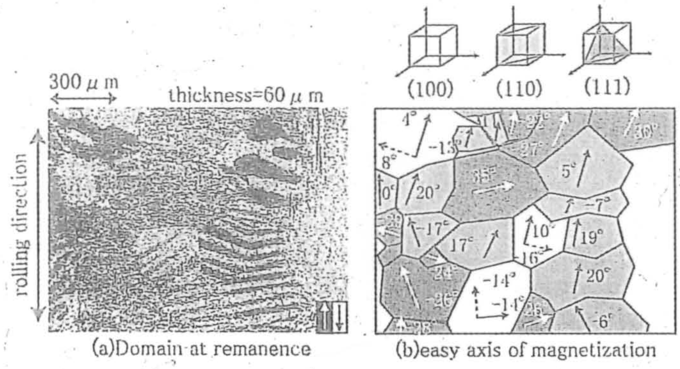

Fig. 2. Domain and easy axis of the Si-Fe (L). Sheet thickness is 60 μm and averaged grain size is 200 μm.

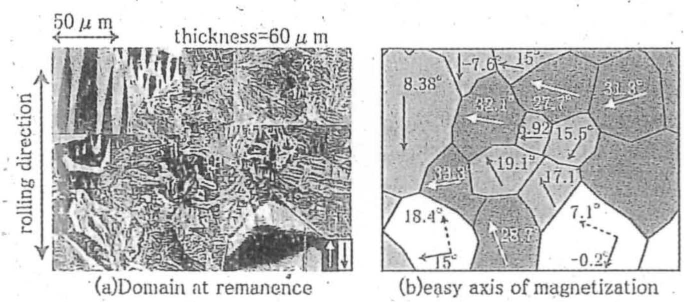

Fig. 3. Domain and easy axis of the Si-Fe (S). Sheet thickness is 60 μm and averaged grain size is 40 μm.

is noted that the stripe domains of grains near (100) and (110) planes couple and run through the grain boundary making a kink. Thus, thinning of the Si–Fe(L) sheet to the thickness less than the grain size enhances the demagnetizing effect normal to the surface and tends to give rise to the closure domain structure. The normal component of magnetization would generate the increase in eddy current loss and result in the increasing anomaly factor [4].

Fig. 3 shows the magnetic domains at the remanent state and direction of the easy axis of individual grain of the thinned 0.06-mm-thick Si–Fe(S) specimen with averaged grain size of 0.04 mm. It is expected that the sheet has the multiple grains in the thickness direction. It is noted here that the magnification of domain picture is six times larger than that in Fig. 2. The Si-Fe(S) specimen has also the grains near (110) plane with the adjacent near (100) plane at a left hand side and middle portion of the picture in Fig. 3(b). But these grains show no stripe domain configuration. Figs. 4 and 5 show the details of domain change of the Si-Fe(S) sheet caused by thinning from 0.5 mm to 0.06 mm. Domain pictures with higher magnification are shown for grains having near (110) plane with the β-angle of about 8° and −7° and near (111) plane at the upper corner of the left-hand side of the domain picture in Fig. 3(a). In the remanent state, two grains near (110) plane of the 0.5 mm thick Si-Fe(S) sheet exhibit coarse irregular domains extending along the easy axis as seen in Fig. 4. This domain configuration changes hardly in an applied field of 1.4 kA/m. Thinning does not cause the significant domain change. The irregular domains are arranged into triangle like parallel domains which can be saturated with a field of 1.4 kA/m as seen in Fig. 5. It is inferred from its running direction that the triangle parallel domain configuration does not have flux closing domain structure underneath the surface.

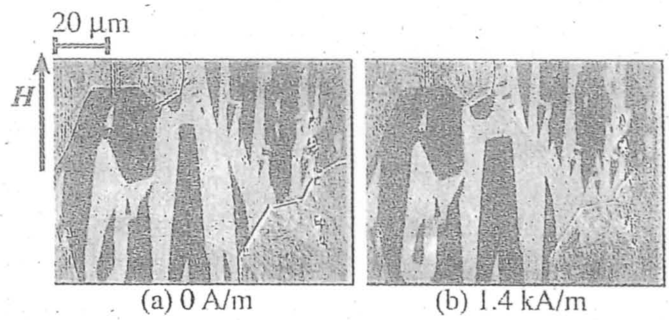

Fig. 4. Domain pattern of a grain having (110) plane at the thickness of 0.5 mm.

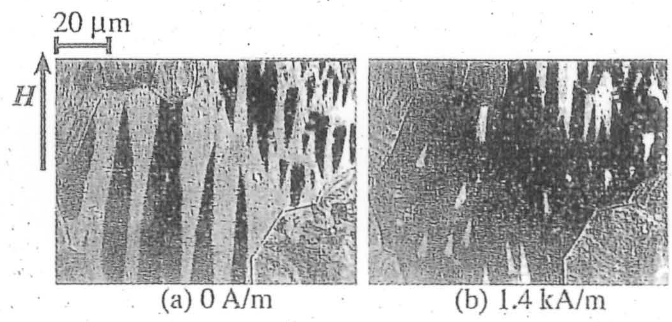

Fig. 5. Domain pattern of a grain having (110) plane at the thickness of 0.06 mm.

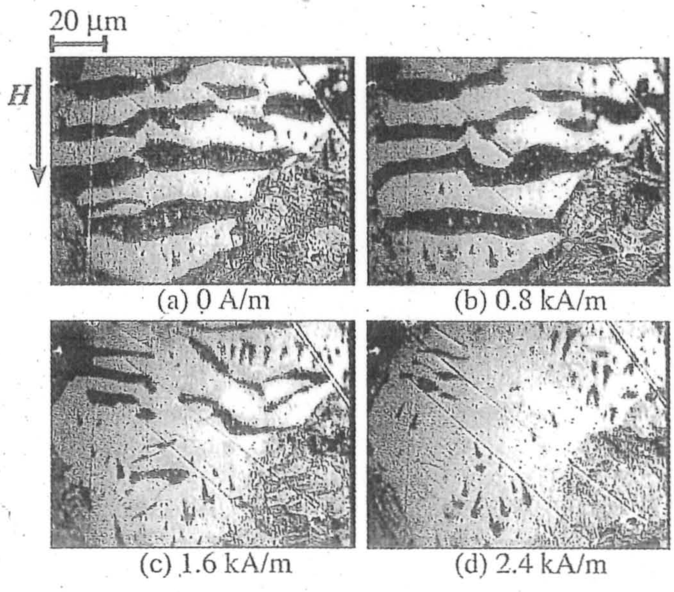

Fig. 6. Domain pattern of a grain having (110) plane at the thickness of 0.05 mm.

The Si–Fe(S) sheet was thinned further to 0.05 mm in thickness. Fig. 6 shows the domains of the same grains as ones shown in Fig. 5. Thinning changed domain pattern drastically. It is seen that the wavy stripe domains extend in the direction transverse to the easy axis and that the stripe domains of two near (110) grains become continuous through the grain boundary. When an external field is applied, the dark domains become narrower and the bright domain reaches saturation leaving the fine dark dagger domains unsaturated. It is inferred from the extending di-

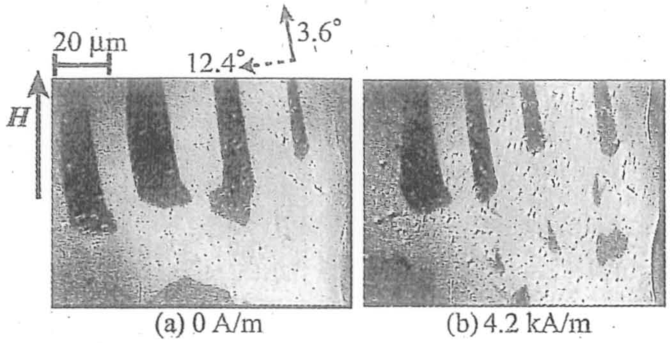

Fig. 7. Domain pattern of a grain having (100) plane at the thickness of 0.5 mm.

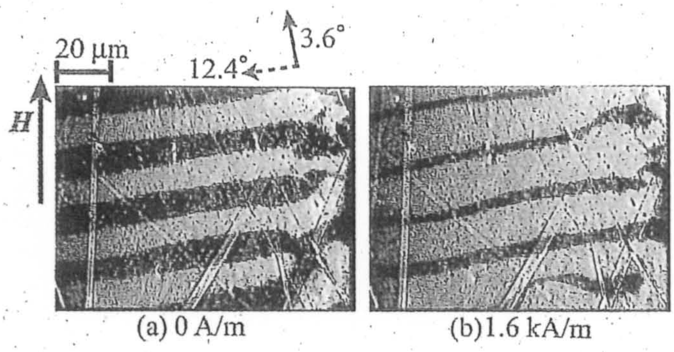

Fig. 8. Domain pattern of a grain having (100) plane at thickness of 0.05 mm.

rection of the domains that the stripe domains reflect also the underneath flux closing domain structure. So that the grain would have thickness comparable to the sheet thickness of 0.05 mm. From this, it is expected that the 0.06 mm thick specimen shown in Fig. 3 has multiple grains in the sheet thickness direction.

Such a drastic domain change was also observed in a grain near (100) plane, whose size is as big as 0.14 mm, as shown in Figs. 7 and 8. The grain has the easy axis close to the sheet surface as shown in the figure. When the sheet is 0.5 mm thick and expected to have multiple grains in the thickness direction, the grain exhibits irregular parallel domains running in the direction of the easy axis, whose ends vanish before reaching the grain boundary. As the sheet is thinned to 0.05 mm in thickness less than the grain size, the irregular parallel domains turn to stripe domain configuration running in the direction transverse to the rolling direction. The domain boundary obscure somewhat compared to that of 0.5 mm thick sheet suggests that the magnetizations in dark and bright domain are heading-on each other. This reflects also the flux closing domain structure underneath the stripe domains at the surface.

IV. Discussion

As seen above, the closure domain structure of the thinned sheet appears when the sheet thickness becomes comparable to the grain size. To suppress the closure domain which gives rise to the excessive eddy current loss, grain refinement to the size less than sheet thickness is necessary. The cubic Si-Fe crystal has the crystalline anisotropy constant of order of 4×10^4 J/m^3 being much higher than that of other soft magnetic materials such as Permalloy. So, the individual grain of the nonoriented electrical sheet would have magnetostatic coupling with adjacent grains through the magnetic charge at the grain boundary. When the Si-Fe sheet has grains more than two in the thickness direction and even one of gains has the easy axis perpendicular to the sheet surface, its perpendicular anisotropy could be relaxed to some extent into sheet plane through the magnetostatic coupling with neighboring grains, since the individual grain of the nonoriented Si-Fe sheet has the easy axis of cube anisotropy at least within angle of 35.2° with respect to the sheet plane. Such an intra-grain coupling would help suppress the formation of flux closing domain structure.

V. Conclusion

The domain structure of the nonoriented Si–Fe electrical sheets with different grain size was observed by decreasing their sheet thickness. It was found that the closure domain structure was suppressed unless the sheet thickness was smaller than the grain size. When the sheet thickness decreased less than grain size, the stripe domain configuration with the underneath flux closing structure appeared in grains having near (110) and (100) plane. The normal magnetization component of the flux closing domain structure would give rise to the excessive eddy current loss. Thus, to eliminate flux closing domain structure, grain refinement is needed. On the other hand, small grains would result in the increase in the hysteresis loss. It is expected that the big flat grains extending in the sheet plane would help decrease the hysteresis loss. Consequently, the thin Si–Fe sheet with a few big flat grains in the thickness direction would be a good candidate for nonoriented Si–Fe materials with low power loss.

References

[1] T. Shimazu and M. Shiozaki, "Effects of grain size and frequency on eddy current loss in Si-Fe sheets," *IEEE Trans. Magn.*, vol. 26, pp. 1972–1974, Sept. 1990.
[2] B. Y. Huang, K. Yamamoto, Y. Yamashiro, and C. Kaido, *J. Magn. Soc. Jpn.*, vol. 23, pp. 1369–1372, 1999.
[3] C. Kaido and T. Wakisaka, *Trans. IEE Jpn.*, vol. 117-A, pp. 685–690, 1997.
[4] M. Takezawa, J. Yamasaki, T. Honda, and C. Kaido, *J. Magn. Magn. Mater.*, vol. 254–255, pp. 167–169, 2003.