(110) grain growth and magnetic properties of thin grain-oriented 3% silicon steel sheets

著者	石山　和志
journal or publication title	IEEE Transactions on Magnetics
volume	35
number	5
page range	3379-3381
year	1999
URL	http://hdl.handle.net/10097/47765

doi: 10.1109/20.800530

(110) Grain Growth and Magnetic Properties of Thin Grain-Oriented 3 % Silicon Steel Sheets

Masaki Nakano and Hirotoshi Fukunaga
Nagasaki University, Nagasaki 852-8521, Japan

Kazushi Ishiyama and Ken Ichi Arai
Tohoku University, Sendai 980-77, Japan

***Abstract*- (110) grain growth and magnetic properties in thin grain-oriented silicon sheets with ultimately low loss were investigated. A final-annealing at 1150℃ for 20min enables us to obtain the thin sheets covered with only (110) grains and consequently the magnetic induction at 800 A/m, B_8, reached 1.9 T.**

***Index terms* – final-annealing condition, magnetic induction at 800 A/m, (110) grain growth, thin-grain-oriented silicon sheets**

I. INTRODUCTION

Thin grain-oriented 3% silicon steel sheets can be prepared by the three-stage rolling method composed of cold-rolling, intermediate-annealing and final-annealing as displayed in Fig.1 [1], [2]. In this method, surface energy is mainly used as a motive force of (110) grain growth [3] instead of grain boundary energy in conventional methods with inhibitors [4], [5]. Although the three-stage rolling method is a promising way to obtain sheet with very low loss, an investigation of (110) grain growth during the final-anneal is needed to develop the process for application to commercial production, i.e. a decrease of final-annealing time (F.A.time). Some experiments about the relationship between (110) grain growth and final annealing conditions have been reported in conventional grain-oriented silicon steel sheets [6]-[8]. In these experiments, however, the results were affected by inhibitors in the control of final texture and then the mechanism of (110) grain growth in the conventional method can not be applied to that of the thin silicon sheets fabricated by the three-stage rolling method.

In this report, we investigated the relationship between (110) grain growth and magnetic properties (coercive force Hc and the magnetic induction at 800 A/m B_8) as the sheets were finally annealed. It became clear that (110) abnormal grains grew dramatically after F.A.time = 0.5 min and thin sheets with $B_8 \cong 1.9$ T can be obtained at F.A.time = 20 min. Further, we investigated the effect of heating rate.

II. EXPERIMENTAL PROCEDURE

The procedure used a three-stage rolling method with

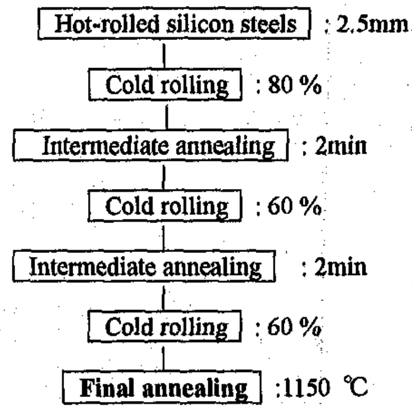

Fig.1 Diagram of three-stage rolling method.

intermediate-annealing at 800 ℃ for 2 min to obtain 80 μm thick rolled sheets from hot-rolled silicon steels and final-annealing to obtain the (110) texture. We selected 80 %, 60 %, and 60 % as the amounts of the three-stage rolling reductions considered in this report, which is one of the optimum conditions [9]. The 80 μm thick rolled sheets were cut into pieces of 100 mm in length and 5-7 mm in width and finally annealed in an infrared furnace at 1150 ℃. The intermediate and final annealings were carried out in a vacuum of 1×10^{-3} Pa. The recrystallized texture of the thin sheets was observed by etch-pits. The static coercive force and the magnetic induction were measured with a dc B-H loop tracer.

III. RESULTS and DISCUSSION

A. (110) Grain Growth and Magnetic Properties in Final Annealing Process

Figure 2 shows the relationship between magnetic properties and final-annealing time. As the annealing time increased, B_8 increased and Hc decreased. The Hc vs. final annealing temperature curve had a sudden drop at F.A.time = 0.5 min. At F.A.time = 20 min, B_8 and Hc of thin sheets were approximately 1.9 T and less than 4 A/m, respectively. Figure 3 shows the dependence of iron loss on magnetic induction in a sample finally annealed at 1150 ℃ for 20min. This figure also shows the previously reported iron

Manuscript received March 2, 1999.
M. Nakano, 81-095-843-7104, fax:81-095-843-7104, mnakano@net.nagasaki-u.ac.jp

0018-9464/99$10.00 © 1999 IEEE

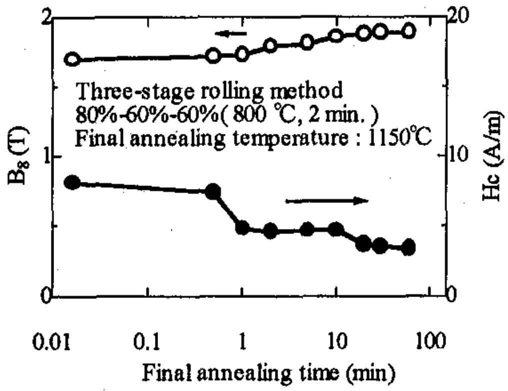

Fig .2 Magnetic induction under applied field of 800 A/m, B_8, and coercive force, Hc, obtained by three-stage rolling method as a function of final annealing time

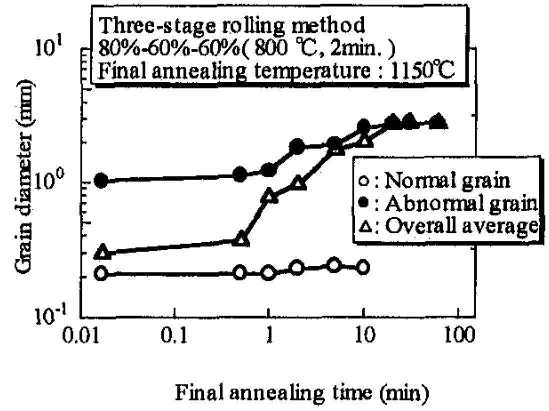

Fig. 4 Grain growth obtained by three-stage rolling method as a function of final annealing time.

loss of a sample annealed at 1150 ℃ for 60 min. The losses of the two sheets were almost the same. The measured iron loss W13/50 under the applied tensile strength of 2 kg/mm^2 was approximately 0.28 W/kg, which is less than that of the conventional (300 μ m) grain-oriented silicon steels by about 50 %.

The (110) grain growth of the above-mentioned sheets is displayed in Figs. 4 and 5. After F.A.time = 0.5 min, abnormal (110) grains grew dramatically and this growth was considered to decrease Hc. F.A.time =20 min was long enough in order to cover the thin sheets with oriented (110) grains. These results indicate that (110) grain-oriented silicon thin sheets with very low loss can be obtained at F.A.time = 20 min.

B. Effect of Heating Rate on Magnetic Properties and [001] Orientation in the Final Annealing Process

The average α angle (the angle between the [001] axis and the rolling direction in the (110) plane) of the above-mentioned sheets was approximately 4~5° [1], which is larger than the average of α, 3°, reported in conventional grain-oriented silicon steels [10]. It is well accepted that a reduction in heating rate or usage of topological gradient of temperature is an effective way to control the grain diameter and to improve [001] orientation in conventional silicon steels. Thus we investigated the effect of heating rate on magnetic properties and [001] orientation of (110) grains.

Figure 6 shows the dependence of heating rate on grain diameter. All samples were prepared under the same cooling rate of approximately 120 ℃/min. The grain diameter slightly increased as the heating rate decreased. As displayed in Fig. 7, B_8 and the [001] orientation did not depend on the heating rate of final annealing. As mentioned previously, the surface energy is mainly used as the motive force of (110) grains in the three-stage rolling method and therefore this different motive force is considered to be the reason for constant B_8 values in Fig. 7.

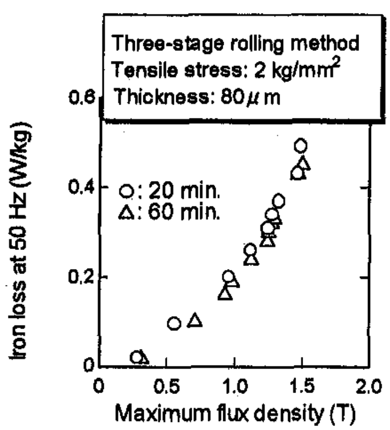

Fig. 3 Magnetic loss of 80 μ m thick grain-oriented silicon steel sheets obtained by three-stage rolling method as a function of maximum flux density

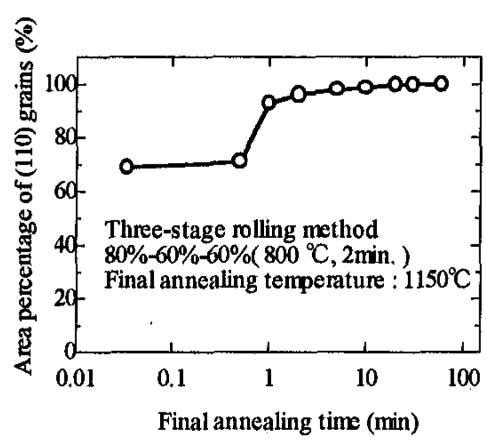

Fig. 5 Area percentage of (110) grains obtained by three-stage rolling method as a function of final annealing time.

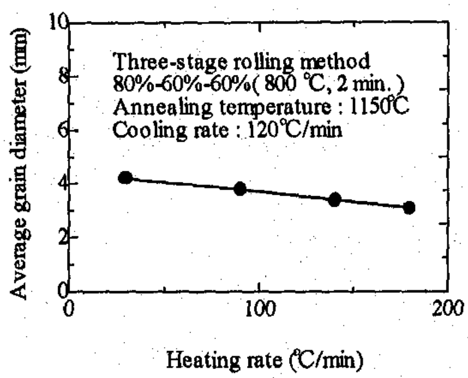

Fig. 6 Average grain diameter obtained by three-stage rolling method as a function of heating rate of final-annealing process.

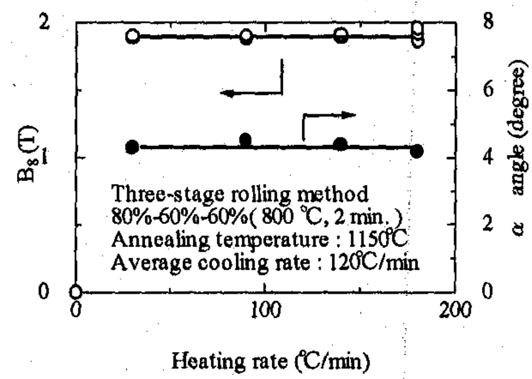

Fig. 7 Magnetic induction under applied field of 800 A/m, B_8, and α angle obtained by three-stage rolling method as a function of heating rate of final annealing process.

IV. Conclusions

Thin grain-oriented silicon steels have been fabricated by a three-stage rolling method and investigated for the (110) grain growth and magnetic properties in the final-annealing process. The obtained results are as follows:

(1) A final-annealing at 1150 ℃ for 20min enables us to obtain thin grain-oriented silicon sheets containing only (110) grains, and consequently the magnetic induction at 800 A/m, B_8, reached 1.9 T.

(2) Magnetic properties and [001] orientation do not depend on the heating rate of a final-annealing process.

References

[1] M. Nakano, K. Ishiyama, K. I. Arai, and H. Fukunaga, "New production method of 100-μ m-thick grain-oriented 3% silicon steel sheets," *J. Appl. Phys.*, vol. 81, pp. 4098-4100, April 1997.

[2] M. Nakanol, K. Ishiyama, K. I. Arai, and H. Fukunaga, "REDUCTION OF IRON LOSS IN THIN GRAIN-ORIENTED SILICON STEEL SHEETS," *IEEE Trans. Magn.*, vol. 33, pp. 3754-3756, September 1997.

[3] M. Nakano, K. Ishiyama, K. I. Arai, and H. Fukunaga, "Construction of (110)[001] Texture in 100-μ m Thick Silicon Steels," *J. Magn. Soc. Japan*, vol. 20, pp. 445-448, 1996. (in Japanese)

[4] K. Kuroki, T. Sato and T. Wada, " Inhibitors for Grain Oriented Silicon Steel," *J. Japan Inst. Metals*, vol. 43, No. 3, pp. 175- 181, August 1978. (in Japanese)

[5] S. Nakajima K. Takahashi, and J. Harase, "Effect of Inhibitor on Secondary Recrystallization of Grain-oriented Electrical Steel Produced by Single-stage Cold Rolling Process," *Tesu-to-Hagane*, vol. 77, No.10, 1991. (in Japanese)

[6] J. Harase and R. Shimizu, " Mechanism of Secondary Recrystallization in Grain Oriented Silicon Steel," *J. Japan Inst. Metals* vol. 54, No. 1, pp. 1-8, 1990. (in Japanese)

[7] J. Harase, R. Shimizu and N. Takahashi, "COINCIDENCE GRAIN BOUNDARY AND (110)[001] SECONDARY RECRYSTALLIZATION IN Fe-3% Si, " *Acta metall mater.* vol. 38, No. 10, pp. 1849-1856, 1990. (in Japanese)

[8] Y. Inokuti and F. Saito, " Configuration of Primary Grains Resistant to Consumption by Secondary Goss Grains," *J. Japan Inst. Metals*, vol. 55, No. 11, pp. 1167-1173, 1991. (in Japanese)

[9] M. Nakano, K. Ishiyama, K. I. Arai, and H. Fukunaga, "Effect of rolling condition on textures and magnetic properties in thin grain-oriented silicon steels, " *Journal de Physique*, pp. 543-546, 1998.

[10] S. Taguchi, T. Yamamoto, and A. Sakakura, " New Grain -Oriented Silicon Steel with High Permeability "ORIENTCORE HI-B" ", *IEEE. Trans. Magn.*, vol. MAG-10, pp. 123-125, 1976.