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Rolled texture and magnetic properties of 3% silicon steel

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Conventional grain-oriented silicon steels 0.3 mm thick were cold-rolled to thicknesses from 0.18 to 0.08 mm, and the magnetic properties and grain textures of these sheets were observed before and after annealing. The results indicated that the magnetic induction B_8 and the coercive force H_c were 1.8 T and 25 A/m, respectively, for a sheet 0.08 mm thick after primary recrystallization. When a 0.12-mm-thick sheet was annealed for more than 6 h at 1200 °C, the tertiary recrystallization had begun, and the (110)[001] texture occupied the whole surface of the sheet. The magnetic properties of this sheet were as follows : $B_8 = 1.97$ T, $H_c = 1.7$ A/m, $W_{12.5/50} = 0.21$ W/kg, and $W_{17/50} = 0.43$ W/kg under the application of a tensile stress of 4 kg/mm^2.

INTRODUCTION

Silicon steels are widely used as magnetic core materials for transformers and rotating machines. In these steels, the reduction of iron loss is the most important problem. In the past, the loss was decreased by increasing the perfection of the (110)[001] grain texture, the so-called Goss texture.[1,2] Recently, in addition to this method, the following new attempts to reduce the loss were carried out : (1) reducing sheet thickness, (2) increasing silicon content, (3) applying an external tensile stress, and (4) scratching the sheet surface. In these methods, a chemically etched thin sheet of grain-oriented silicon steel was reported to have an extremely low loss comparable to that of amorphous materials.[3]

In this paper, we report the grain texture and magnetic properties of thin silicon steel sheets obtained by rolling followed by annealing.

EXPERIMENT

Conventional grain-oriented silicon steels, 0.3 mm in thickness, were cold-rolled to thicknesses from 0.18 to 0.08 mm by a rolling machine having a roll diameter of 50 mm, after an insulation coat on the steel surface was removed by dissolution in a solution of hydrofluoric acid and sulfuric acid. The thin silicon steels obtained were cut into pieces 100 mm long and 5 mm wide and annealed in a vacumm of 1.3×10^{-3} Pa using an infrared image furnace. In this annealing, the heating rate was 3 °C/s, and the cooling rate was about 10 °C/s down to 600 °C. The crystallographic grain texture of thin sheets after being rolled and annealed was observed by x-ray diffraction. The average grain diameter was determined by surface observation using an optical microscope. The static magnetic properties were measured by using a B-H loop tracer. The iron loss was measured by using a single sheet tester at 50 Hz.

RESULTS AND DISCUSSION

Because the rolled grain texture is known to have strong effects upon the grain growth by annealing, the as-rolled texture was observed for thin sheets with thicknesses of 0.18, 0.12, and 0.08 mm. Figure 1 shows x-ray pole figures of the surface and of the inside of the sheets. In this experiment, the inside pole figures were observed using sheets which had a surface layer removed by chemical etching in a solution of hydrofluoric acid and hydrogen peroxide to produce thicknesses of a half of the as-rolled sheets. The main grain texture of the sheet 0.18 mm thick is the (110)[001] at the inside as well as the surface. In the sheet 0.12 mm thick, although the surface maintains the (110)[001] texture, the inside texture changes to the $(111)[11\bar{2}]$. In the 0.08 mm thick sheet, the $(111)[11\bar{2}]$ texture also appears on the as-rolled sheet surface, and becomes more sharp at the inside of the sheet. Figure 2 shows the dependence of the intensity ratio (I_{222}/I_{110}) of x-ray diffraction on the sheet thickness reduced by chemical etching. In this figure, it is found that as the measured point diffraction approaches the center of the sheet thickness, the (110) diffraction becomes weaker, while the (222) diffraction becomes stronger. The higher the roll reduction rate is, the more pronounced this tendency becomes. These

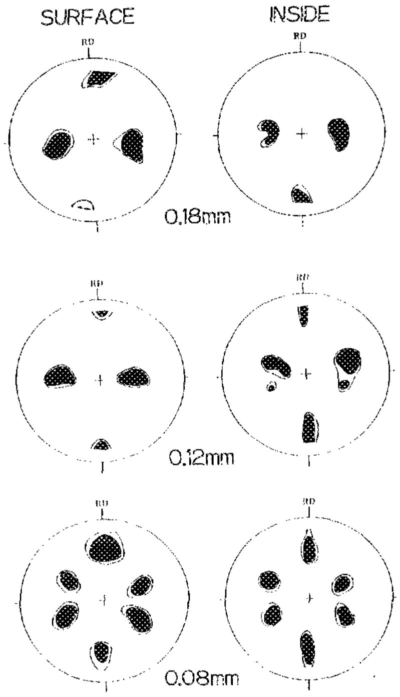

FIG. 1. (200) pole figures at the surface and inside of as-rolled sheets with thicknesses of 0.18, 0.12, and 0.08 mm.

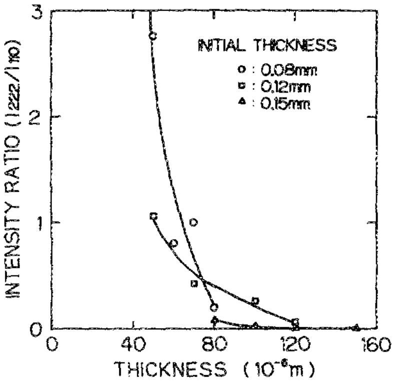

FIG. 2. X-ray intensity ratio of chemically etched sheets with initial as rolled thicknesses of 0.15, 0.12, and 0.08 mm.

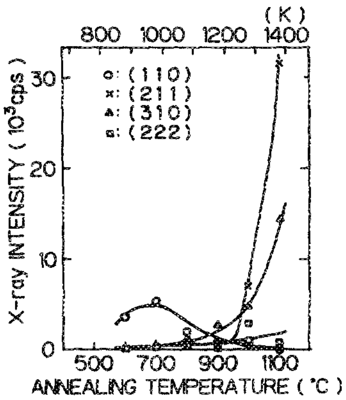

FIG. 4. X-ray intensity as a function of the annealing temperature.

facts also mean that the grain texture of silicon steel is changed by rolling from the (110)[001] to the (111)[11$\bar{2}$] near the center of the sheet thickness at the beginning; the area with the (111)[11$\bar{2}$] texture spreads toward the sheet surfaces with increasing in the amount of roll reduction and finally the area reaches the sheet surface.

By annealing at 700 °C for 1 h, primary recrystallization of all sheets was accomplished. The nucleation temperature and the average grain size differed with the sheet thicknesses. Figure 3 shows pole figures and B-H loop of the primary recrystallized sheet with thickness of 0.08 mm. In this figure, the primary grain texture is the (110)[001], and the magnetic induction B_8 is a high 1.8 T. In this sheet, however, the average grain size is so small (<0.1 mm) that the coercive force H_c is a large 25 A/m.

Figure 4 shows the dependence of the x-ray diffraction intensity of I_{110}, I_{211}, I_{310}, and I_{222} on the annealing temperature for sheets 0.1 mm thick. At 700 °C, the intensity of the (110) diffraction is the strongest in all diffractions. When the annealing temperature is increased, the secondary recrystallization begins, and the primary (110) grains are changed to new grains with crystal planes of (211), (310), and (222).

Figure 5 shows the dependence of magnetic induction B_8 and coercive force H_c upon the annealing temperature in a sheet 0.08 mm thick. The coercive force H_c became smaller with increasing the annealing temperature and reached 8 A/m above 1000 °C. At these temperatures the sheet was occupied completely with secondary grains with sizes ten times larger than that of the primary grains. On the other hand, the B_8 became a small 1.67 T with an increase in the annealing temperature, because the degree of concentration of the [001] crystal axis along the roll direction in secondary grains is extremely low.

Figure 6 shows the dependence of magnetic induction B_8 and coercive force H_c of a sheet 0.12 mm thick upon the annealing time at 1200 °C. In this figure, a drastic change was observed for the sheet annealed above 3 h. The magnetic induction B_8 increased to an extremely high 1.95 T and at the same time the coercive force H_c decreased to a low 1.7 A/m. This behavior is caused by the tertiary grain growth, that is to say, (110)[001] grains among the secondary grains grew rapidly and finally occupied the whole surface of the sheet. The iron loss of the tertiary recrystallized sheet with and without the application of a tensile stress was observed at 50 Hz. As a result, the loss $W_{17/50}$ was 0.71 W/kg without a stress, and decreased to 0.43 W/kg with a stress of 4 kg/mm². The loss $W_{12.5/50}$ was 0.21 W/kg under the stress and this value was almost the same as that of amorphous materials.

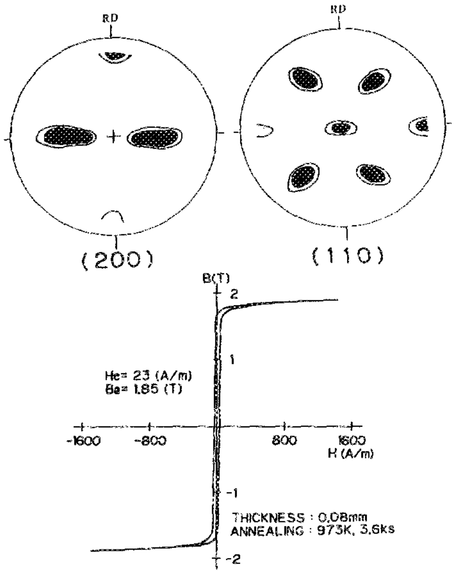

FIG. 3. Pole figures and B-H loop of a primary recrystallized sheet 0.08 mm thick.

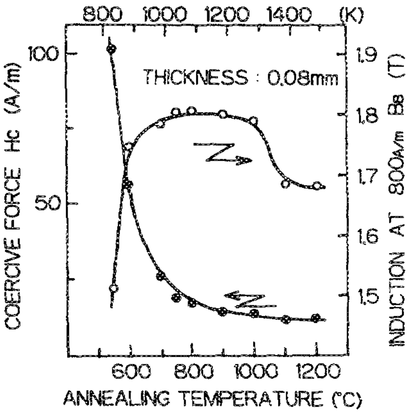

FIG. 5. Magnetic induction B_8 and coercive force H_c at 800 A/m as a function of the annealing temperature.

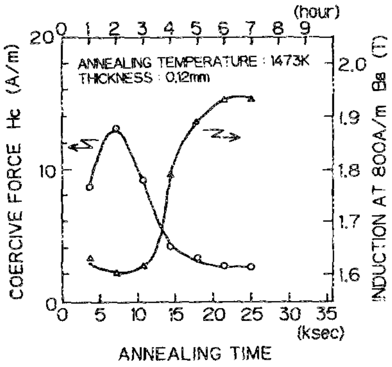

FIG. 6. Magnetic induction B_8 and coercive force H_c at 800 A/m as a function of the annealing time.

SUMMARY

Conventional grain-oriented silicon steels were cold-rolled to thicknesses from 0.18 to 0.8 mm and annealed in a vacuum. The grain texture and magnetic properties of these sheets were observed at room temperature and results obtained summarized as follows:

(1) By rolling the grain-oriented silicon steel, the grain texture changes from the (110)[001] to the (111)[11$\bar{2}$], with an increase in the amount of cold reduction.

(2) After annealing at 700 °C, primary recrystallization with the (110)[001] texture was completed, and magnetic induction B_8 and coercive force H_c in a sheet 0.08 mm thick were 1.8 T and 25 A/m, respectively. When the sheet was annealed above 1000 °C, the secondary recrystallization was observed, and the coercive force H_c became smaller (8 A/m), however, the magnetic induction B_8 also became smaller (1.6 T).

(3) When a sheet 0.12 mm thick was annealed for more than 6 h at 1200 °C, the tertiary recrystallization had begun, and the (110)[001] grains among the secondary grains grew and finally occupied the whole surface of the sheet. The magnetic properties of the sheet after tertiary recrystallization were as follows: $B_8 = 1.97$ T, $H_c = 1.7$ A/m, and $W_{12.5/50}$ and $W_{17/50}$ were 0.21 and 0.43 W/kg under the application of a tensile stress of 4 kg/mm^2.

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