Development of Low-Loss Grain-Oriented Silicon Steel

Y. Ushigami, H. Masui, Y. Okazaki, Y. Suga, and N. Takahashi

Grain-oriented silicon steel has evolved through improvement of {110}<001> orientation, development of thinner-gage material, and development of magnetic domain refining techniques. Core loss in the material has been dramatically reduced over the past 40 years. To further improve core loss, mobile domain walls must be increased by reducing the pinning sites, and surface closure domains must be decreased by improving {110}<001> orientation. When these technologies are industrialized, a core-loss reduction of 25% is expected at 1.7 T for 0.23 mm thick grain-oriented silicon steel.

Keywords
core loss, grain-oriented silicon steel, magnetic domain

1. Introduction

GRAIN-ORIENTED silicon steel is a soft magnetic material used for both stacked and wound transformer cores. Environmental protection regulations have necessitated energy savings and noise reduction for transformers, leading to a demand for low-core-loss and low-magnetostriction grain-oriented silicon steel.

In 1934, Goss invented the manufacturing process for grain-oriented silicon steel (Ref 1). The American Rolling Mill Company subsequently developed this process on an industrial scale (Ref 2). In Japan, Yawata Iron and Steel Corporation (a former division of Nippon Steel Corporation) introduced this technology and started its production in 1953. This paper reviews developments in core-loss reduction technology and the progress made toward developing lower-core-loss products.

2. Development of Grain-Oriented Silicon Steel

Figure 1 outlines the historical development of core-loss reduction technology. The first commercial production of silicon steel was hot-rolled silicon steel. It can be seen that the invention of grain-oriented silicon steel dramatically improved core loss. Figure 2 shows the progress in core-loss reduction made by Nippon Steel Corporation (NSC). Core loss of the latest NSC products has been reduced to less than one-third of that achieved in grain-oriented silicon steel produced in 1953. This core-loss reduction has been accomplished primarily by (1) improvement of {110}<001> alignment, (2) development of thinner-gage material, and (3) development of magnetic domain refining techniques.

Figure 3 and Table 1 summarize the improvements in core loss in terms of hysteresis and eddy-current loss (Ref 3). Total core loss was first reduced by the improvement of orientation with the invention of "ORIENTCORE HI-B" (Ref 4). The {110}<001> alignment was improved from 7° to 3° and magnetic induction (B8) increased from 1.82 T(CGO) to 1.92 T(HI-B), which decreased hysteresis loss (e.g., 0.19 W/kg at 1.7 T). Hysteresis loss decreases monotonously with the improvement of {110}<001> orientation sharpness, which is represented by the increase in magnetic induction at the magnetic field of 800 A/m (B8). However, eddy-current loss increases with the improvement of {110}<001> sharpness due to increased domain wall spacing. Therefore, total core loss (hysteresis loss + eddy-current loss) saturates and takes a minimum value around the magnetic induction (B8) of 1.95 T, as shown in Fig. 4 (Ref 5). Development of technologies to decrease eddy-current loss was the point of the research at that time.

From these studies, thinner-gage product with a thickness of 0.23 mm was developed in 1982 by overcoming the metallurgical instability of secondary recrystallization. Comparing 0.30 and 0.23 mm thick HI-B, the classical eddy-current loss was improved by 0.15 W/kg at 1.7 T due to the decrease in thickness. Anomalous eddy-current loss was improved by magnetic domain refining techniques of laser irradiation, which is more effective for highly grain-oriented silicon steel (Ref 6).

This laser-irradiated material (ZDKH) was applied only for stacked-type transformer cores and cannot be used for wound cores. As the effect of magnetic domain refining by laser irradiation is due to the local stress, its effect vanishes when stress-relief annealing is performed, which is indispensable for wound transformer cores. Therefore, a heat-proof domain-refining method due to grooves and micrograins was developed; this type of material (ZDMH) has been reproduced since 1988 (Ref 7). With the introduction of these domain-refining techniques, the anomalous eddy-current loss was decreased by 0.1 W/kg at 1.7 T. Figure 5 and Table 2 present typical magnetic property values for current NSC products.

3. Domain Structure of Grain-Oriented Silicon Steel

In the pursuit of ideal grain-oriented silicon steel, the dynamic behavior of magnetic domain wall movement has been investigated by high-voltage scanning electron microscopy (SEM). The ideal model of magnetic domain wall movement assumes that all domain walls consist of 180° walls and they move homogeously at the same speed. However, this is not the case.

Dynamic observation of domain wall movement has revealed that it is affected by magnetic defect structures. These consist primarily of two components: (1) pinning of 180° wall movement and (2) creation and annihilation of surface closure domains.

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3.1 *Pinning of Domain Wall Movement*

The domain walls can be pinned by defect structures such as rough surfaces, nonmetallic inclusions, and crystal defects. A nonmagnetic oxide (forsterite and spinel) film (Ref 8) formed on the subsurface of grain-oriented silicon steel (Fig. 6) provides sites for domain wall pinning. Figure 7 (Ref 9) shows the dynamic observation of domain wall movement of a 3%Si-Fe single crystal in nearly ideal orientation with the oxide film. It is evident that movement of the domain wall is not uniform. Figure 8 (Ref 9) shows the dynamic domain structure of a 3%Si-Fe single crystal in nearly ideal orientation with a surface

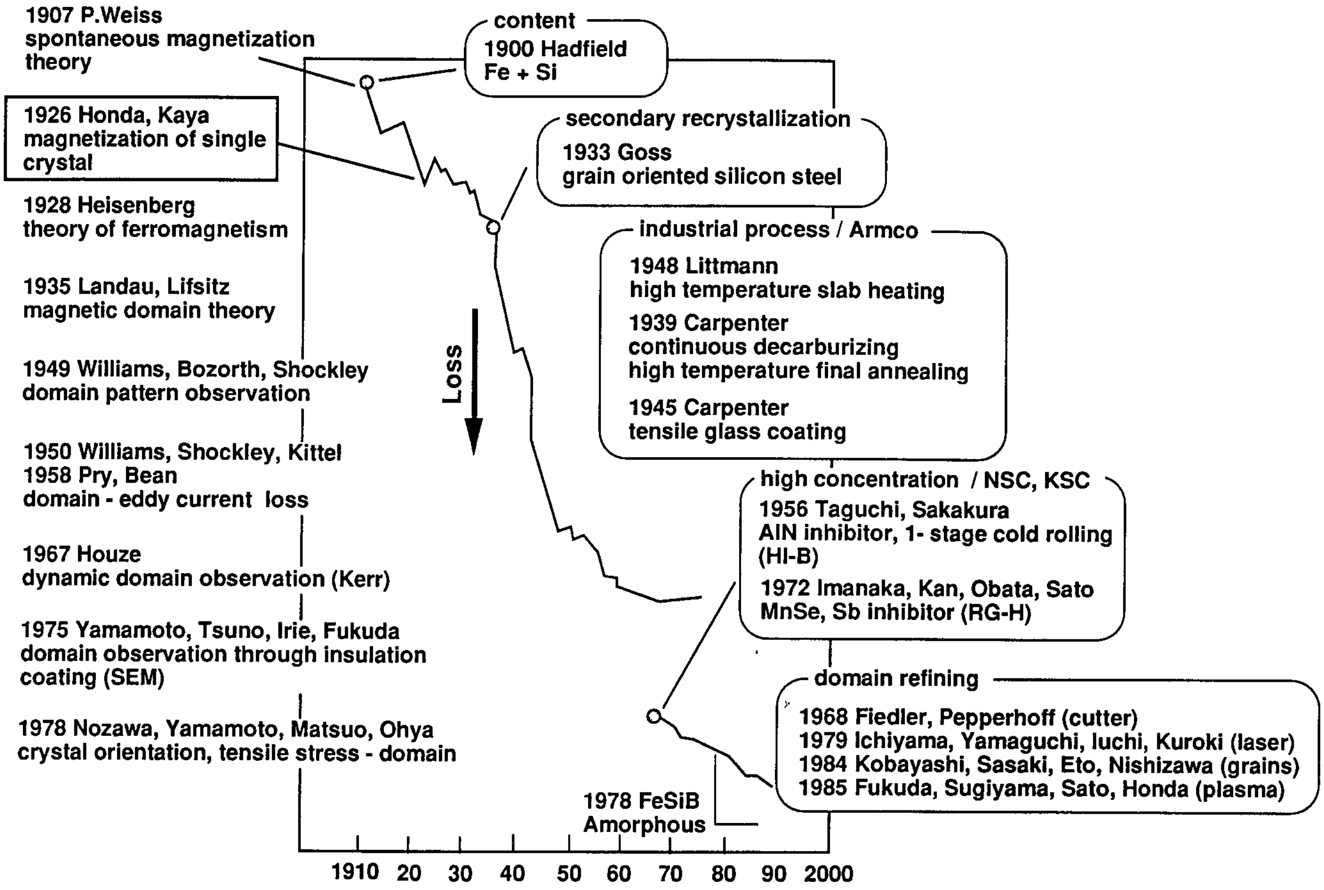

Fig. 1 Historical development of core-loss reduction technology in grain-oriented silicon steel

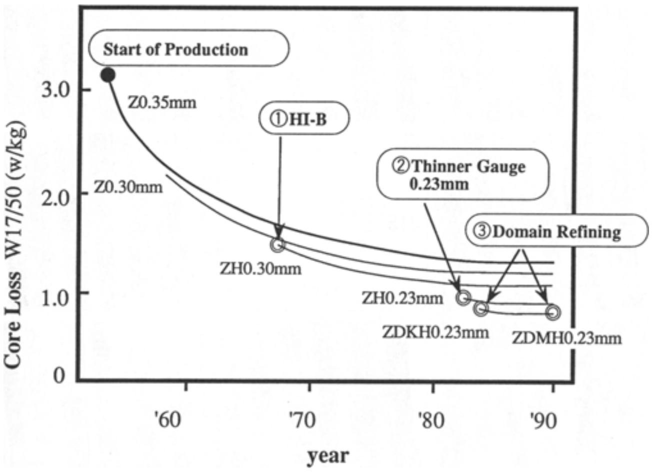

Fig. 2 Development of core-loss reduction in grain-oriented silicon steel by Nippon Steel Corporation. Z, CGO; ZH, HI-B; ZDKH, domain-refined HI-B (laser); ZDMH, domain-refined HI-B (heat proofed)

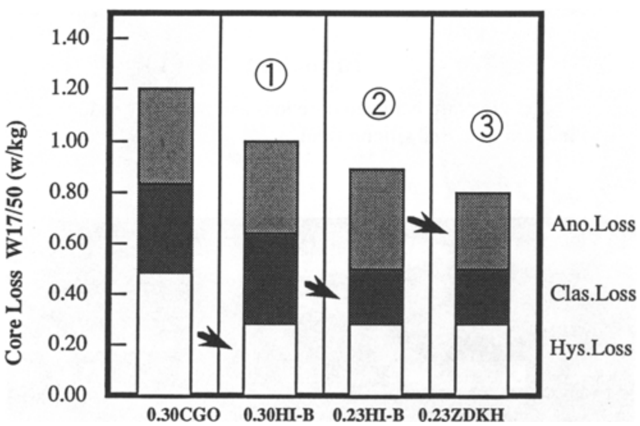

Fig. 3 Improvements in core loss in terms of hysteresis and eddy current loss. Circled numbers refer to the corresponding processes in Fig. 2.

made smooth by chemical polishing. In contrast to Fig. 7, domain wall movement is homogeneous and magnetization is uniform.

It also was revealed that secondary recrystallized grains can contain substructures (e.g., subboundaries) that are substantially formed during the secondary recrystallization process (Fig. 9) (Ref 10, 11). Domain walls can interact with these defect structures (Fig. 10) (Ref 12).

Technology for reducing these pinning sites is necessary to improve hysteresis loss and anomalous eddy-current loss.

3.2 *Surface Closure Domain*

Figure 11 shows the dynamic observation of a crystal tilted 4.5° from the ideal {110}<001> orientation with the surface oxide film (Ref 13). It can be seen that surface closure (lancet) domains are created and annihilated during the magnetization process, which results in increased hysteresis loss and anomalous eddy-current loss.

It has been demonstrated that the area of closure domain is related to the tilt angle of the crystal orientation, as shown in Fig. 12 (Ref 9). Therefore, technology for controlling the tilt angle to less than 3°, which means the development of highly oriented silicon steel (B8 >1.92 T), is necessary to improve losses in hysteresis and anomalous eddy current by minimizing the surface closure domains.

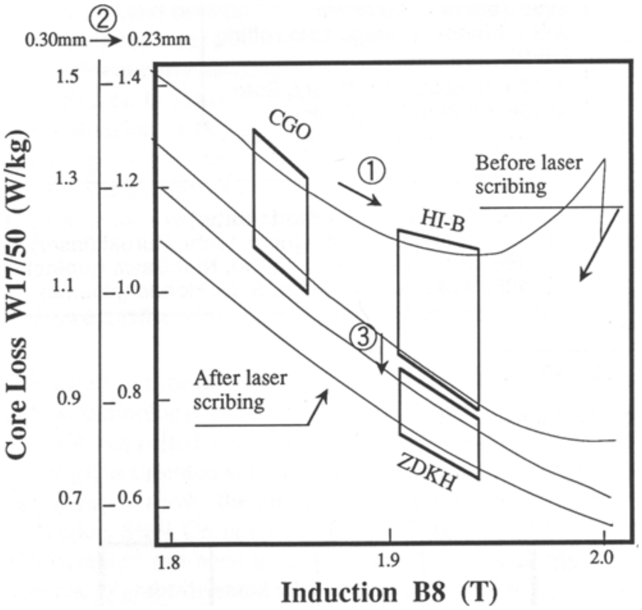

Fig. 4 Relationship between core loss and magnetic induction (B8) in grain-oriented silicon steel

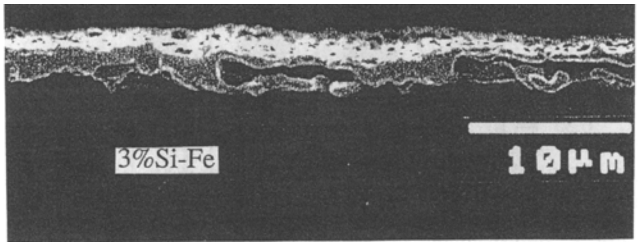

Fig. 6 Structure of surface oxide film observed by SEM (section)

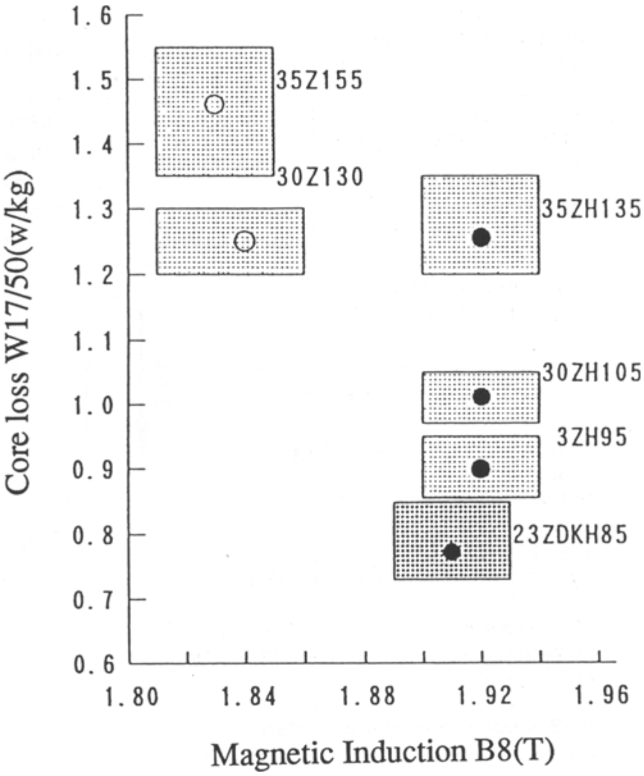

Fig. 5 Standard of grain-oriented silicon steel and typical magnetic property values for current NSC products

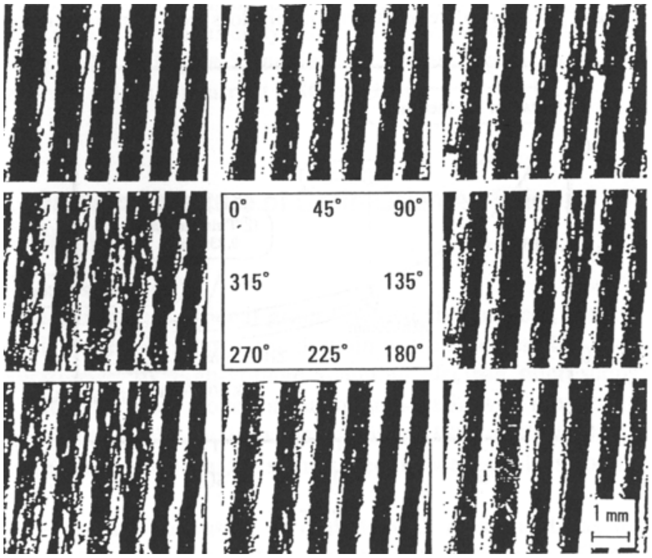

Fig. 7 Dynamic observation of domain wall movement of a 3%Si-Fe single crystal in nearly ideal {110}<001> orientation with the surface oxide film

4. Further Development of Grain-Oriented Silicon Steel

As discussed previously, control of two magnetic features is necessary to further improve core loss: (1) increasing mobile domain walls by reducing the pinning sites and (2) decreasing surface closure domains by improving the {110}<001> orientation alignment.

Work in terms of secondary recrystallization has rapidly progressed, with establishment of the mechanism of orientation selectivity (Ref 14, 15) and development of new technologies for controlling secondary recrystallization (Ref 16). It has been demonstrated that the interaction between precipitates and grain boundaries is the dominant factor in orientation selectivity and that the secondary recrystallization temperature is the most important parameter in the control of secondary recrystallization.

Based on these findings, research is currently under way to develop a new processing method. Figure 13 shows the quantitative estimation of core-loss improvement with the results of 0.23 mm thick 3.2% Si products manufactured by the labora-

Table 1 Improvement in core loss in terms of hysteresis and eddy-current loss ($W_{17/50}$)

Material	Thickness, mm	Hysteresis loss, W/kg	Classical eddy-current loss, W/kg	Anomalous eddy-current loss, W/kg	Total loss, W/kg
CGO	0.30	0.48 (40%)	0.36 (30%)	0.36 (30%)	1.20 (100%)
HI-B	0.30	0.29 (28%)	0.36 (34%)	0.40 (38%)	1.05 (100%)
	0.23	0.29 (32%)	0 21 (23%)	0.40 (45%)	0.90 (100%)
ZDKH	0.23	0.29 (36%)	0.21 (26%)	0.30 (38%)	0.80 (100%)

Table 2 Standard of grain-oriented silicon steel and typical magnetic property values for current NSC products

Material	Thickness, mm	Core loss at 50 Hz, W/kg			Core loss at 60 Hz, W/kg			Magnetic induction (B8), T
		1.3 T	1.5 T	1.7 T	1.3 T	1.5 T	1.7 T	
Z (CGO)	0.35	0.74	1.01	1.46	0.93	1.33	1.90	1.83
	0.30	0.64	0.86	1.25	0.80	1.12	1.60	1.84
	0.27	0.59	0.79	1.15	0.73	1.03	1.48	1.85
ZH (HI-B)	0.35	0.72	0.95	1.27	0.95	1.26	1.69	1.92
	0.30	0.56	0.74	1.01	0.74	0.98	1.32	1.92
	0.27	0.53	0.70	0.96	0.68	0.92	1.25	1.92
	0.23	0.48	0.64	0.90	0.61	0.83	1.16	1.92
ZDKH	0.27	0.52	0.66	0.89	0.66	0.88	1.16	1.92
	0.23	0.42	0.56	0.77	0.55	0.75	1.01	1.91
ZDMH	0.23	0.42	0.56	0.77	0.55	0.75	1.01	1.91

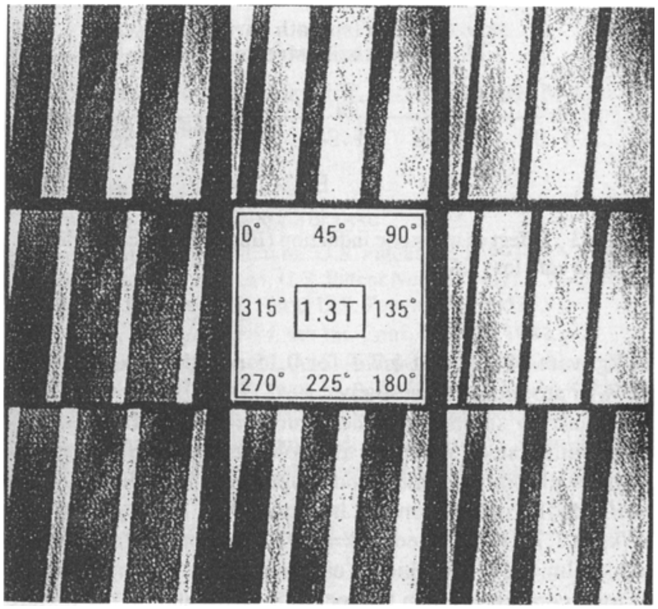

Fig. 8 Dynamic observation of domain wall movement of a 3%Si-Fe single crystal in nearly ideal {110}<001> orientation with a chemically polished surface

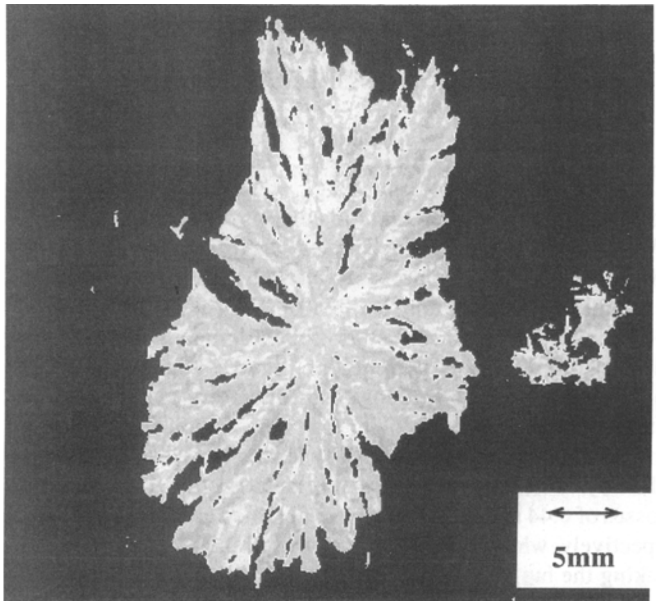

Fig. 9 Substructure in a secondary recrystallized grain of 3%Si-Fe observed by synchrotron x-ray topography

Fig. 10 Pinning of domain wall by substructure in a secondary recrystallized grain observed by optical Kerr microscopy

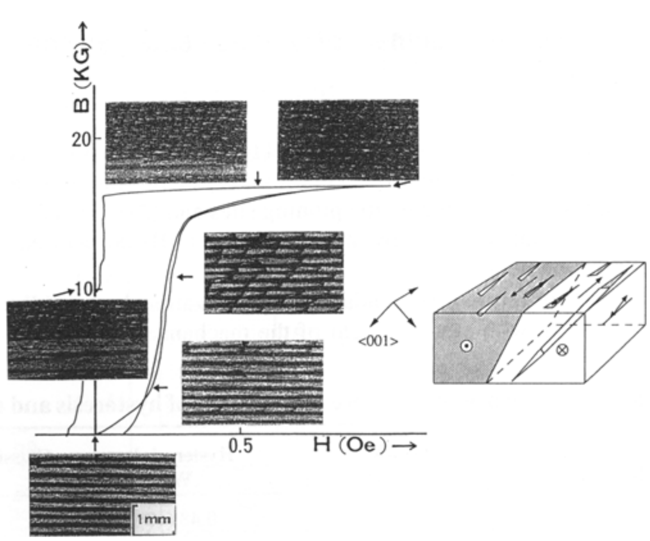

Fig. 11 Dynamic observation of domain wall movement of 3%Si-Fe single crystal tilted 4.5° from the ideal {110}<001> orientation with the surface oxide film

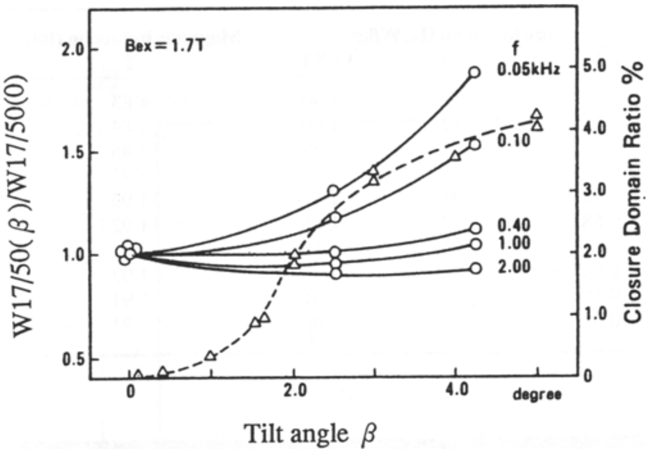

Fig. 12 Effect of tilt angle of crystal on core loss (normalized by the core loss of the ideal orientation) and the area of surface closure domains

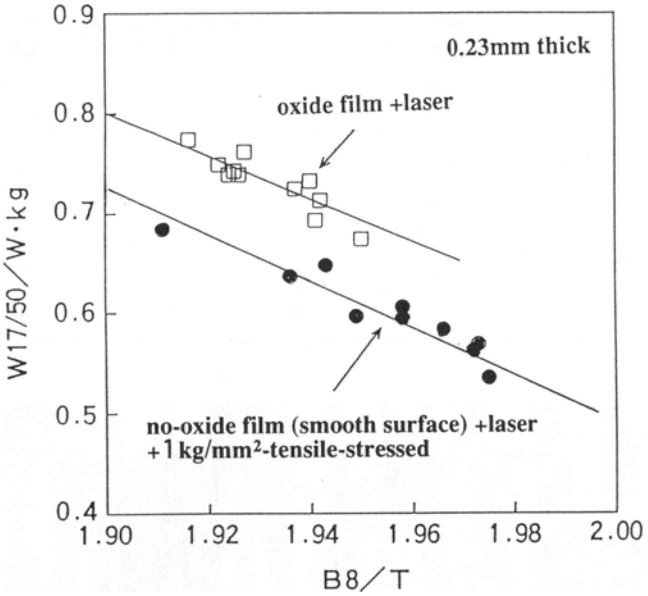

Fig. 13 Effect of magnetic induction (B8) and surface condition on core loss

tory line. It can be seen that the core loss is decreased by 0.1 W/kg at 1.7 T when pinning sites are decreased. Increasing the B8 value of 0.4 T by sharpening the {110}<001> alignment is estimated to decrease core loss by 0.1 W/kg at 1.7 T.

Product thickness is another important parameter for controlling classical eddy-current loss. Figure 14 shows the effect of sheet thickness on core loss with laboratory-made 2.93% Si steel specimens (B8 = 1.99 T) that were chemically polished, laser irradiated, and mechanically tensile stressed (1 kg/mm^2) (Ref 5). When the thickness was reduced to 0.15 mm, core losses of 0.44 and 0.25 W/kg were obtained at 1.7 and 1.3 T, respectively, which is equivalent to that of the amorphous metal taking the building factor into account. In the laboratory line, when the secondary recrystallization was stabilized and magnetic flux density (B8) was 1.97 T, with the 3.2% Si and 3.5% Si product of 0.15 mm thickness, core losses of 0.38 and 0.35 W/kg were obtained at 1.7 T for 0.15 mm thick 3.2% Si and 3.5% Si products, respectively.

Figure 15 summarizes the future prospects for grain-oriented silicon steel. When the technologies for removing the domain wall pinning sites and improving the alignment of {110}<001> orientation are industrialized, core loss of 0.55 W/kg at 1.7 T is expected (B8 = 1.97 T, smooth surface with no oxide film, 3.2% Si), which is estimated as a 25% improvement of total core loss. When the technology for stabilizing texture control by secondary recrystallization also is established for the thinner-gage 3.5% Si product of 0.15 mm thickness, core loss of 0.35 W/kg at 1.7 T is expected.

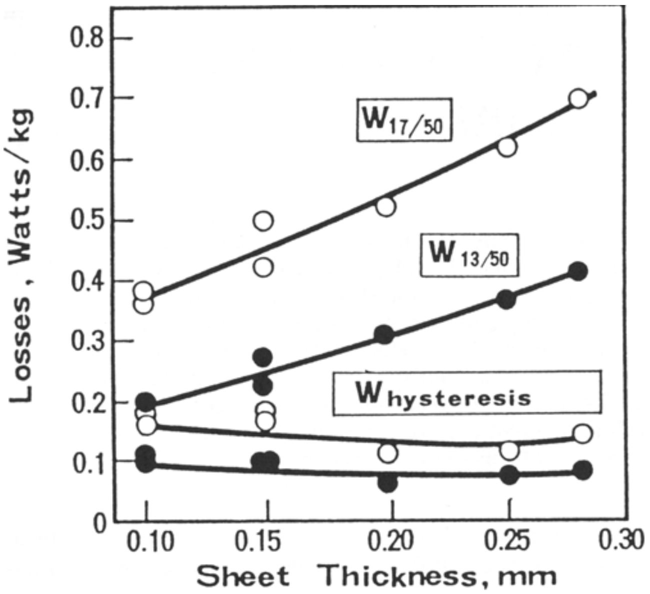

Fig. 14 Effect of sheet thickness on core loss in 2.93% Si steel (B8 = 1.99 T). The samples were chemically polished, laser irradiated, and tensile stressed (1 kg/mm^2).

5. Summary

The development of core-loss reduction is reviewed. A combination of metallurgical and physical approaches has dramatically reduced core loss over the past 40 years.

To further improve core loss, mobile domain walls must be increased by reducing pinning sites, and surface closure domains must be decreased by improving {110}<001> orientation. With the development of industrial techniques for minimizing such magnetic defect structures, a core-loss reduction of 25% is expected at 1.7 T for 0.23 mm thick grain-oriented silicon steel.

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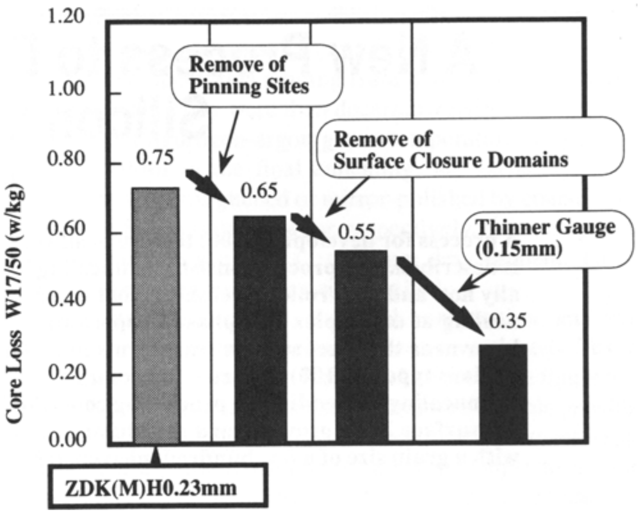

Fig. 15 Future prospects for core-loss reduction in grain-oriented silicon steel