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The Effects of Grain Size on the Magnetic Properties of Nonoriented Electrical Steel Sheets

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Abstract. The effects of grain size on magnetic properties of nonoriented electrical steel sheets were investigated at the commercial power of frequency (50 Hz). The permeability, magnetic induction, and core loss of test specimens were optimal at their intermediate grain sizes. (LC) core loss $W_{15/50}$ of Epstein specimens was minimum at a grain diameter of approximately 150 μm, regardless of the silicon content. A study of the relationship between magnetic properties and grain size of ring specimens showed that core loss, magnetic induction, and ac permeability were optimal at larger grain diameters in a weak magnetic field and at smaller grain diameters in a strong magnetic field. It was found that magnetic induction and ac permeability tended to improve at large grain diameters in the irreversible magnetization range and at small grain diameters in the rotation magnetization range.

INTRODUCTION

The effect of grain size on magnetic properties of silicon steel was first studied by W.E. Ruder in 1912, who discovered that the hysteresis loss decreased as the grain size is coarsened [1]. Since then, researchers such as T.D. Yensen have studied the effect of grain size on magnetic properties [2–4]. However, the results of their researches are not universally applicable, since they are essentially subject to the effects of steel purity and oxidized surface layer. This paper discusses the effects of grain size on the magnetic properties of nonoriented electrical steel sheets based on measurement data in diverse magnetic fields and on data obtained from literature published in the past.

TEST METHODS

Five types of specimens with different silicon content were used (Table 1). Specimens 1 to 4 were prepared by cold rolling hot rolled sheets once or twice (with temper rolling) into a final thickness of 0.50 mm and then annealing them under various conditions in a dry atmosphere of H_2 and N_2 to obtain various grain sizes. Specimen 5 was prepared by annealing and cold rolling a hot rolled sheet to a final thickness of 0.50 mm and then annealing it in the same dry atmosphere to obtain various grain sizes. Grain diameters were calculated from the numbers of grains through the thickness of specimens. Core loss $W_{15/50}$ was measured on half lengthwise and half transverse Epstein specimens. Only Specimen 3 made up of 30 ring cores (O.D. 90 mm, I.D. 74 mm) was punched, stress-relief annealed, laminated, wound with primary and secondary windings of 200 turns each, and tested for magnetic properties (core loss, magnetic induction, and permeability) at 50 Hz. The inside diameter to outside diameter ratio of the ring core is set at 0.82, because if this ratio exceeds 0.82, the magnetizing force H will be determined within 1.0% [5].

RELATIONSHIP BETWEEN GRAIN SIZE AND LC CHARACTERISTIC

All electrical steel sheets show minimum LC (half lengthwise and half transverse to the rolling direction) core loss $W_{15/50}$ at a grain diameter of approximately 150 μm, regardless of their silicon content (Fig. 1). With the data about LC magnetic induction and LC permeability obtained from Epstein specimens, it is extremely difficult to derive their dependency or grain size. As the grains grow, the texture changes and the oriented grains favorable for magnetic properties gen-

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Table 1. Composition of Specimens (wt%)

	C	Si	Mn	P	S	Al	O
Specimen 1	0.005	0.01	0.50	0.07	0.003	0.001	0.012
Specimen 2	0.005	0.30	0.30	0.07	0.005	0.001	0.012
Specimen 3	0.006	0.81	0.29	0.09	0.002	0.218	0.001
Specimen 4	0.005	1.10	0.25	0.02	0.005	0.200	0.001
Specimen 5	0.002	3.00	0.22	0.02	0.001	1.000	0.001

erally tend to disappear. As a result, the magnetic induction and permeability are significantly influenced by the texture. This means that the magnetic properties fluctuate under the influence of material hysteresis and conditions for grain-coarsening annealing, making it difficult to obtain the relationship between grain size and magnetic properties.

RELATIONSHIP BETWEEN GRAIN SIZE AND RING CORE CHARACTERISTICS

To obtain the relationship between core loss W and grain diameter d, a regression equation was defined:

$$W = a_0 + a_1 \cdot d^{1/2} + a_2 \cdot d^{-1/2} \tag{1}$$

The optimum grain diameter giving the minimum core loss can be calculated from the point of inflection in Eq. (1). Thus,

$$d = a_2/a_1 \tag{2}$$

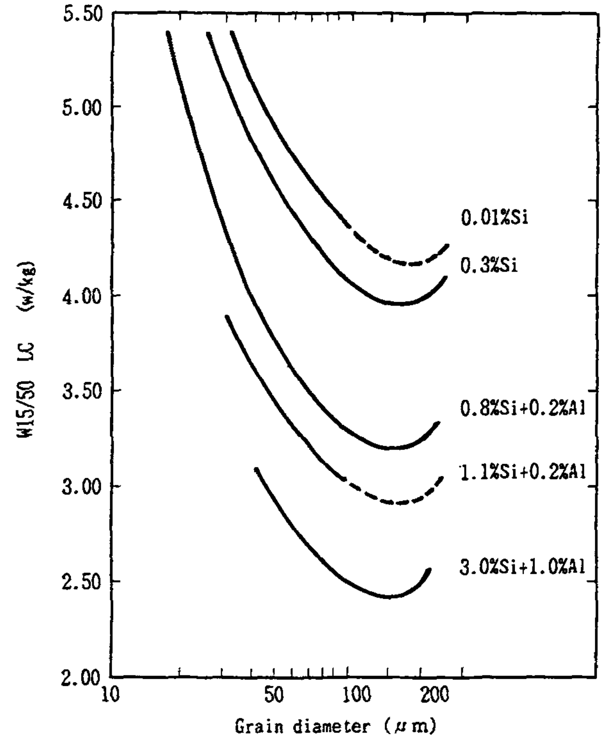

Fig. 1. Effect of grain size on LC core loss $W_{15/50}$.

The reason Eq. (1) was adopted is that the regression equation that adds hysteresis loss $Wh \propto d^{-1/2}$ and eddy current loss $We \propto d^{1/2}$ is the most accurate. Values obtained by Eqs. (1) and (2) are shown in parentheses in Table 2. With respect to magnetic induction and permeability, an attempt was made to apply regression Eqs. (3) to (5) with a view to determining their relationship with grain size.

$$B \text{ or } \mu = a_0 + a_1 \cdot d^{1/2} + a_2 \cdot d^{-1/2} \tag{3}$$

$$B \text{ or } \mu = a_0 + a_1 \cdot d^{-1} + a_2 \cdot d^{-2} \tag{4}$$

$$B \text{ or } \mu = a_0 + a_1 \cdot (\log d) + a_2 \cdot (\log d)^2 \tag{5}$$

However, unlike the relationship between core loss and grain size, the relationship of magnetic induction and permeability with grain size was such that optimal grain diameter could not be calculated systematically. This is considered due to the difficulty involved in linear regression of magnetization and permeability curves as compared with the linear regression of core loss curve. Therefore, optimal grain diameters (Table 2) were obtained from data scatter diagrams (Figs. 2, 3). Figures 5 to 7 show the relationships of optimal grain size with ring core ac magnetization curve, ac permeability curve, and core loss curve, respectively.

Effect of Grain Size on Magnetic Induction (Figs. 2 and 5)

In the irreversible magnetization range, the domain wall is considered to discontinuously shift from one stable position to another. The magnetic induction range $B_{0.8}$ to B_2 (Ir = 0.5 to 0.67 $\cdot Is$) is considered to fall within the irreversible magnetization range, suggesting that a relatively large grain diameter (210 μm) with few domain walls gives favorable magnetic induction. Ir and Is mean residual magnetization and saturation magnetization, respectively. In the rotation magnetization range beyond the irreversible magnetization range, the shift of domain walls has been completed and the magnetization is considered to take place as the result of rotations from the "easy direction" of magnetization [6]. The magnetic induction range B_3 to B_{300} (Ir = 0.71 to 0.88 $\cdot Is$) is considered to fall within this rotation magnetization range. In this case, a relatively small grain diameter (50 μm) gives favorable magnetic induction. Small grain diameters are advantageous because they facilitate the (100)(0vw) orientation grains having many easy direction of magnetization to be retained on the plane. These grains

Table 2. Grain Size Providing Best Magnetic Properties

Induction	Grain Diameter	ac Permeability	Grain Diameter	Core Loss	Grain Diameter
$B_{0.8}$	210 μm	$\mu_{5/50}$	210 μm	$W_{5/50}$	230 (226)[a] μm
B_1	210 μm	$\mu_{6/50}$	210 μm	$W_{6/50}$	230 (259) μm
$B_{1.5}$	210 μm	$\mu_{7/50}$	210 μm	$W_{7/50}$	230 (229) μm
B_2	210 μm	$\mu_{8/50}$	210 μm	$W_{8/50}$	230 (228) μm
B_3	70 μm	$\mu_{9/50}$	210 μm	$W_{9/50}$	230 (233) μm
B_5	50 μm	$\mu_{10/50}$	210 μm	$W_{10/50}$	230 (240) μm
B_8	50 μm	$\mu_{11/50}$	210 μm	$W_{11/50}$	230 (234) μm
B_{10}	50 μm	$\mu_{12/50}$	210 μm	$W_{12/50}$	220 (220) μm
B_{25}	50 μm	$\mu_{13/50}$	210 μm	$W_{13/50}$	220 (221) μm
B_{50}	50 μm	$\mu_{14/50}$	90 μm	$W_{14/50}$	190 (187) μm
B_{80}	50 μm	$\mu_{15/50}$	50 μm	$W_{15/50}$	150 (153) μm
B_{100}	50 μm	$\mu_{16/50}$	50 μm	$W_{16/50}$	140 (144) μm
		$\mu_{17/50}$	50 μm	$W_{17/50}$	130 (129) μm
		$\mu_{18/50}$	50 μm	$W_{18/50}$	110 (113) μm

[a] Figures in parentheses were obtained by calculations using Eq. (1).

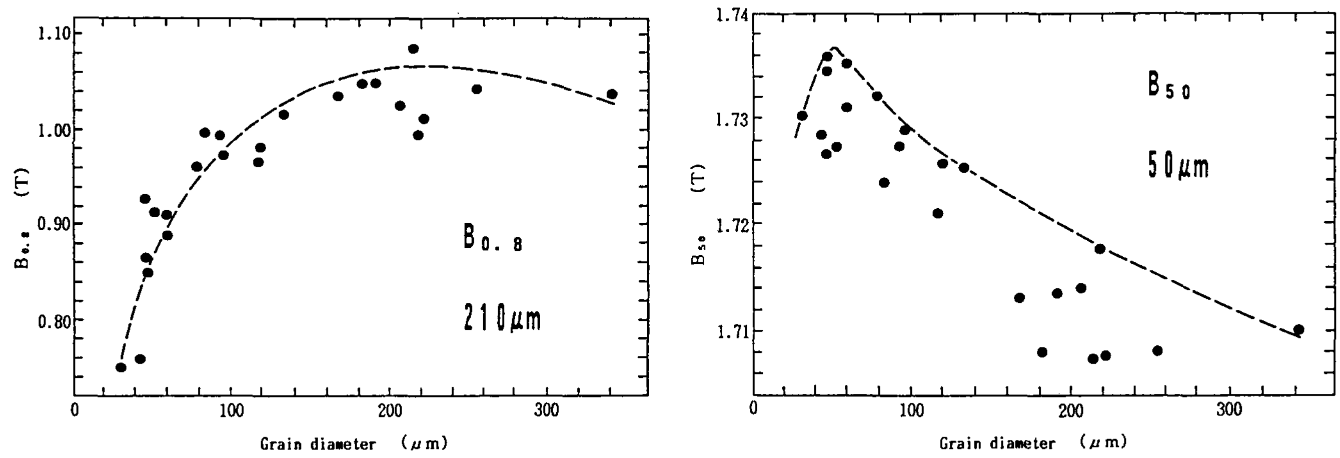

Fig. 2. Effect of grain size on magnetic induction in ring cores.

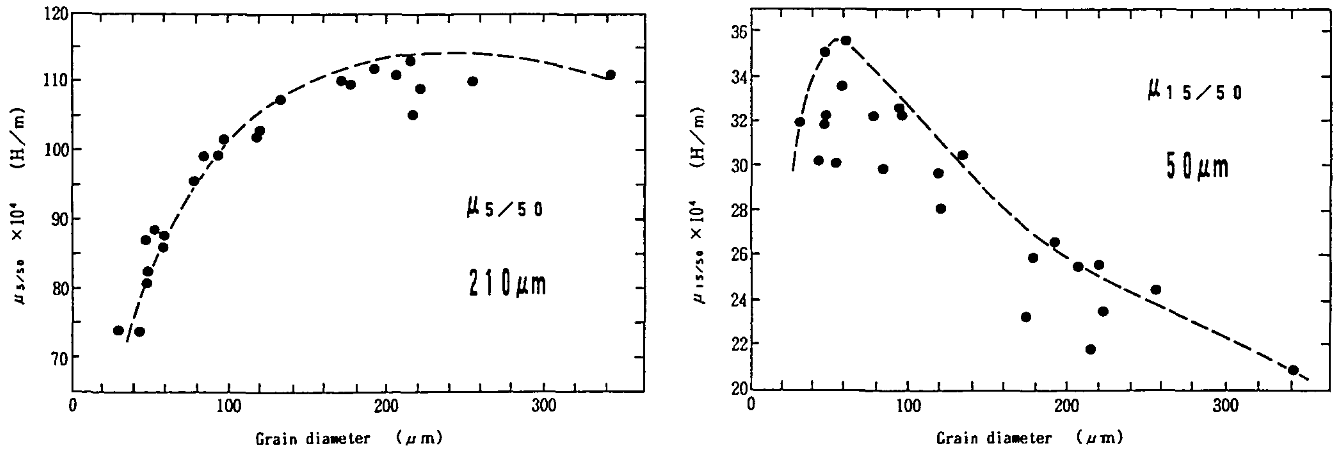

Fig. 3. Effect of grain size on ac permeability in ring cores.

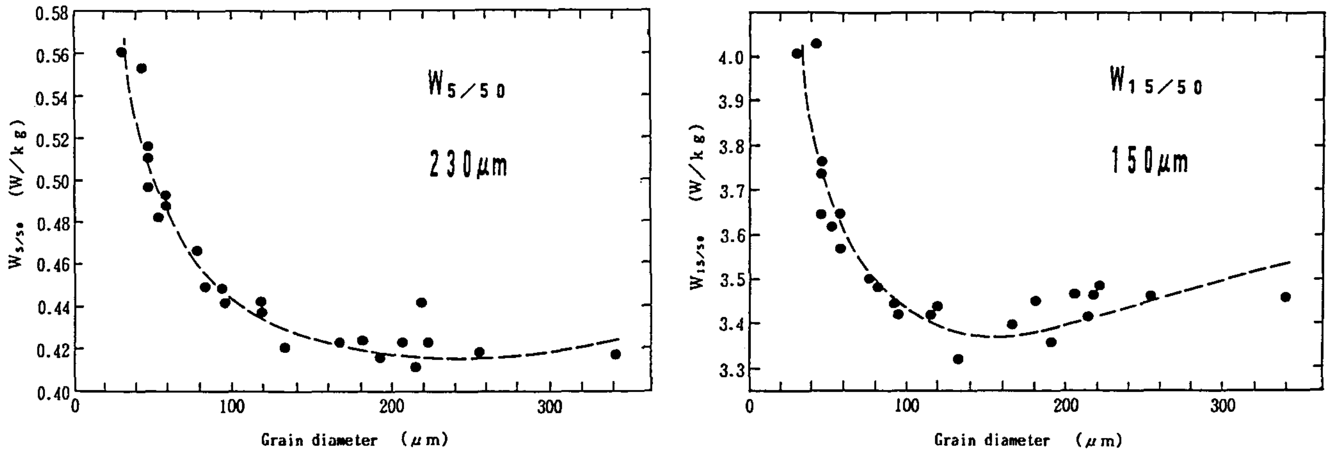

Fig. 4. Effect of grain size on core loss in ring cores.

tend to disappear as grains grow normally. This coincides with the fact that magnetic induction in a strong magnetic field deteriorates as the grains are coarsened.

Effect of Grain Size on ac Permeability (Figs. 3 and 6)

In weak magnetic fields of $\mu_{13/50}$ or less, a large grain diameter (210 μm) offers favorable ac permeability, whereas in stronger magnetic fields of $\mu_{15/50}$ or more, a small grain diameter (50 μm) offers favorable ac permeability. Since B_3 corresponds to 1.5 T, the basic concept is the same as that applied to magnetic induction. The fact that the optimal grain diameter varies according to magnetic field measured suggests that the magnetic induction and permeability curves change according to grain size.

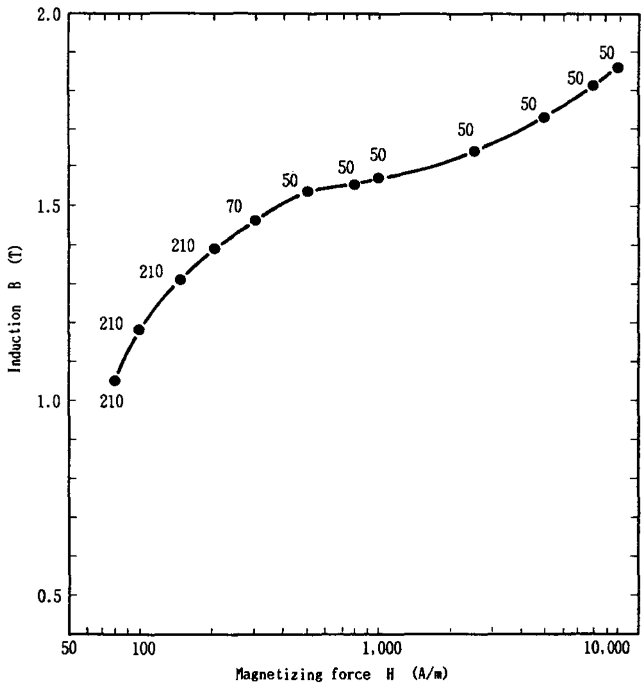

Fig. 5. Relationship between ring core ac magnetization curve and optimal grain size. Note: Each number means a grain diameter (μm) to attain $B_{\max}$.

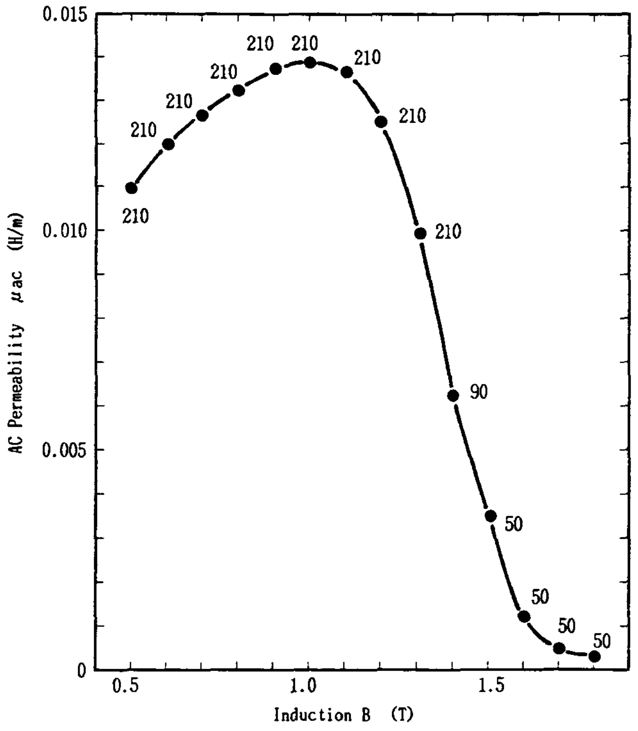

Fig. 6. Relationship between ring core ac permeability curve and optimal grain size. Note: Each number means a grain diameter (μm) to attain $\mu_{\max}$.

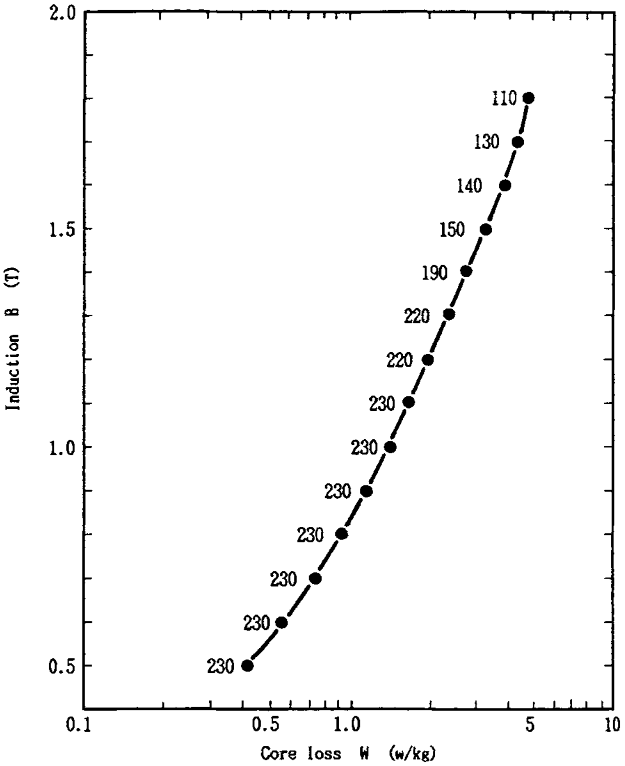

Fig. 7. Relationship between ring core core loss curve and optimal grain size. Note: Each number means a grain diameter (μm) to attain W_{min}.

Effect of Grain Size on Core Loss (Figs. 4 and 7)

In weak magnetic fields of $W_{14/50}$ or less, large grain diameters (220 to 230 μm) offer minimum core loss, whereas in strong magnetic fields of $W_{15/50}$ or more, the optimal grain diameter decreases gradually (190 to 110 μm). In the case of core loss, the dependency of hysteresis loss and eddy current loss on grain size varies, hence the effect of grain size on core loss shows a pattern different from the patterns of effects of grain size on magnetic induction and ac permeability.

COMPARISON WITH PAST EXPERIMENTAL DATA

Relationship Between Core Loss and Grain Size

Table 3 summarizes 12 reports referring to grain sizes which should offer minimum core loss in electrical steel sheets. The data given in Table 3 indicates that minimum core loss is obtained at a grain diameter of 130 to 220 μm regardless of silicon content. Generally speaking, the weaker the magnetic field, the larger tends to become the optimal grain diameter. The following section discusses why the optimal grain diameter offering minimum core loss deviates.

Table 3. Grain Size Offering Minimum Core Loss

Report No.	Si (wt%)	Thickness	Core Loss	Optimal Grain Size	Remarks
7 (1972)	0		$W_{10/60}$	169 μm	
			$W_{15/60}$	163 μm	
8 (1973)[a]	~3	0.5 mm	$W_{10/50}$	Between 240 and 260 μm	Electric-arc furnace
			$W_{15/50}$	ditto	
	~3	0.5 mm	$W_{10/50}$	Between 370 and 390 μm ditto	Open-hearth furnace (substantial amounts of sulfides and oxides)
9 (1977)	3.2	0.5 mm	$W_{10/50}$	Between 175 and 275 μm	
10 (1979)	2	0.5 mm	$W_{10/50}$	Approximately 180 μm	Core loss 1 + C + 2·45 deg (average)
11 (1981)	0	0.5 mm	$W_{15/60}$	Between 50 and 190 μm	
12 (1981)	1.85	0.5 mm	$W_{15/50}$	Approximately 90 μm	
	2.8	0.5 mm	$W_{15/50}$	Approximately 110 μm	
	3.2	0.5 mm	$W_{15/50}$	Approximately 140 μm	
13 (1982)	3.2	0.5 mm	$W_{15/50}$	Between 100 and 150 μm	
14 (1984)	3.2	0.5 mm	$W_{10/50}$	Approximately 150 μm	
15 (1984)	~2	0.53 mm	$W_{15/60}$	Between 50 and 200 μm	
16 (1985)	3.2	0.5 mm	$W_{15/50}$	Approximately 110 μm	Ordinary steel
	3.2	0.5 mm	$W_{15/50}$	Approximately 150 μm	Super high purity steel
17 (1987)	0	0.61~	$W_{10/60}$	180 μm	
		0.71 mm	$W_{15/60}$	130 μm	
			W_{15} DC	100 μm	
18 (1987)	3.3–3.5	0.5 mm	$W_{15/50}$	Approximately 100 μm	

[a] Hot rolled electrical steel sheets.

Deviation of Optimal Grain Size Toward Larger Side. The deviation of optimal grain size toward the larger side is considered to occur when the steel has low purity and large hysteresis loss. As described before, the hysteresis loss is proportional to $d^{-1/2}$ (d: grain size) and the eddy current loss is proportional to $d^{1/2}$. Thus, as the absolute value of hysteresis loss increases, the optimal grain size that gives minimum core loss shifts toward the larger side. This should be understandable by comparison between the data obtained by Zaydman et al. [8], and Candiotti et al. [9] on 3.2% silicon steel (showing poor absolute value of core loss) and the data obtained by Shimanaka et al. [12], Matsumura et al. [14], and Honma et al. [16] (showing good absolute value of core loss).

Deviation of Optimal Grain Size Toward Smaller Side. When grains are coarsened by the normal grain growth, the steel has to be annealed at high temperatures for a long time. In this case, the oxide layer formed on the steel surface normally becomes conspicuous. When the oxide layer on the steel surface increases, the core loss tends to increase as well [19]. Therefore, as an oxide layer is formed on the steel surface, the adverse effect thereof causes the core loss deterioration to occur early in the grain coarsening process. As a result, the minimum core loss appears at a smaller grain size. This phenomenon is verified by the data of Honma et al. [16], which shows that the grain size giving minimum core loss is approximately 150 μm for steel with a thin oxide layer and approximately 110 μm for steel with a thick oxide layer. The above-mentioned fact suggests that the data of Shimanaka et al. [12] on 1.85% silicon steel and 2.8% silicon steel indicating that the optimal grain size is smaller for lower silicon steel is possibly influenced by an oxide layer formed on the steel surfaces.

Effect of Texture. No quantitative data about the effect of texture have been available. As a matter of fact, the texture changes as the grains grow. Since the hysteresis loss increases or decreases as the texture changes, the effect of grain size should be studied with magnetic induction is kept constant. At present, however, there is no experimental method for varying the grain size without changing the texture or magnetic induction. When the grain size is approximately 50 μm or less, the (100)[0vw] orientation grains are partly retained. When the grain size exceeds approximately 80 μm, however, those grains begin to disappear suddenly and the grain orientation assumes near random orientation. Generally speaking, as the grains are coarsened, the magnetic induction and permeability in a strong magnetic field tend to worsen. For example, when the grain size increases from 30 μm to 150 μm, the magnetic induction in terms of B_{50} deteriorates as much as about 0.04 to 0.05 T. Strictly speaking, when the magnetic induction deteriorates, the core loss deteriorates, too. Therefore, in determining the relationship between core loss and grain size, the magnetic induction should be taken into account as a variable. Nevertheless, such a strict data analysis has not been implemented to date.

Relationship Among Magnetic Induction, Permeability, Coercive Force, and Grain Size

Table 4 summarizes seven reports which refer to the relationship among magnetic induction, permeability, coercive force and grain size in nonoriented electrical steel sheet. Of the seven reports, two indicate maximum permeability at intermediate grain sizes. These results were obtained from lamination steels containing no silicon. According to Stephenson et al. [17], their equation for correction calculation gave a grain size of 360 μm for the maximum permeability of $\mu_{10/60}$ and a grain size of 60 μm for the maximum permeability of $\mu_{15/60}$. It is interesting to note that in the present experiment on ring specimens of 0.8% silicon steel, the permeability of $\mu_{15/50}$ became maximum at a grain size of approximately 50 μm—close correlation to the above-mentioned result. In the present study using ring specimens, the effect of texture could be measured on the plane, hence more accurate information could be obtained. As a result, it was found that in weak magnetic fields, larger grain diameters are favorable for magnetic induction and permeability, and that in strong magnetic fields, optimal magnetic properties are obtained at a grain diameter of approximately 50 μm.

SUMMARY

1. Permeability, magnetic induction, and core loss become optimum in a certain grain size range of a given material. In weak magnetic fields, the magnetic properties tend to become optimum at large grain diameters. In weak magnetic fields, coarse grains are considered favorable for magnetic induction and permeability, since the effect of domain wall rotations increases. In strong magnetic fields, on the other hand, fine grains with high degree of integration of (100)[0vw] are considered favorable for magnetic induction and permeability, since the effect of texture is substantially great.
2. LC core loss $W_{15/50}$ is minimum at a grain diameter of approximately 150 μm regardless of silicon content.
3. The relationship between circumferential magnetic properties and grain size was clarified using ring

Table 4. Relationship Among Magnetic Induction, Permeability, Coercive Force, and Grain Size

Report No.	Si (wt%)	Thickness	Property	Optimal Grain Size	Remarks
7 (1972)	0		$\mu p_{10/60}$ ac	160 μm	
			$\mu p_{15/60}$ ac	The larger the grain size, the smaller becomes the value.	
8 (1973)	~3	0.5 mm	B_{25} ac	ditto	
10 (1979)	2	0.5 mm	Hc	ditto	
11 (1981)	0	0.5 mm	$\mu p_{15/60}$ ac	ditto	
13 (1982)	3.2	0.5 mm	Hc	ditto	
16 (1985)	3.2	0.5 mm	B_{50} ac	ditto	Correction calculation gives 360 μm and 60 μm.
17 (1987)	0	0.61~	$\mu p_{10/60}$ ac	Between 130 and 160 μm	
		0.71 mm	$\mu p_{15/60}$ ac	Between 90 and 160 μm	
			μp_{15} dc	Between 130 and 160 μm	

specimens. In weak magnetic fields of B_2 or less, the optimal grain size for magnetic induction is approximately 210 μm, whereas in stronger magnetic fields, the optimal grain size is approximately 50 μm. As for ac permeability, the optimal grain size is approximately 210 μm for $\mu_{10/50}$ and approximately 50 μm for $\mu_{15/00}$. In weak magnetic fields of $W_{11/50}$ or less, core loss is minimum at a grain diameter of approximately 230 μm. In stronger magnetic fields of $W_{15/50}$ or more, however, core loss is minimum at a grain diameter of 150 μm. Thus, the stronger the magnetic field, the smaller tends to become the optimal grain size.

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