

Magnetic Properties of Thin Gauge 3% Si-Fe with {110}⟨001⟩ Orientation

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Thin-gauge 3% Si-Fe with {110}⟨001⟩ orientation is a suitable material for magnetic devices in the frequency range from 10^2 to 10^5 Hz. Low core loss and high permeability in this frequency range are required. With recently developed, highly grain-oriented materials, physical parameters that affect core losses were investigated as a function of excitation frequency and magnetic flux density. The relationship between core loss and excitation conditions is classified into four regions. This material is useful for transformers and inductors, especially for higher flux density application in the middle frequency region (Bm[maximum excitation magnetic flux density] > 1 T, 10^2 to 10^3 Hz), such as airplane devices.

Keywords
electric steels, recrystallization, silicon steels, texture

1. Introduction

THIN-GAUGE 3% Si-Fe with {110}⟨001⟩ orientation is a suitable material for magnetic cores in middle and high frequency use (10^2 to 10^5 Hz). Compared with other materials, ferrites and amorphous metals, thin-gauge 3% Si-Fe has higher saturation magnetization and higher permeability, which makes cores smaller. Low core loss and high permeability in this frequency range are required.

In 1949, M.F. Littmann (Ref 1) invented a noninhibitor process for developing thin gauge 3% Si-Fe with {110}⟨001⟩ orientation. Grain-oriented electrical steel was used as a starting material. After the surface glass film was removed by pickling, the material was cold rolled to the final thickness and annealed for primary recrystallization. B8, magnetic flux density at magnetic field of 800 A/m, was 1.6 to 1.8 T.

In Japan, Yawata Iron and Steel Corporation introduced this technology and started its production in the 1950s. After that, Nippon Kinzoku Corporation started its production in 1966. With the history shown in Table 1, Nippon Kinzoku Corporation is presently the only manufacturer of this material in Japan.

The magnetic properties of this material are standardized by the Japanese Electrical Manufacturers' Association, JEM1239. The products are classified by sheet thickness: 25, 50, and 100 μm. Core loss and magnetic flux density, B8, are guaranteed for each class. Table 2 shows the standard and the typical values of the present products (Ref 2). These thin-gauge 3% Si-Fe products have been applied to high frequency transformers, pulse transformers, inductors, and so forth.

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During the 40 years after the invention, no significant development was performed to this material. In 1988, highly grain-oriented thin-gauge 3% Si-Fe with the magnetic flux density,

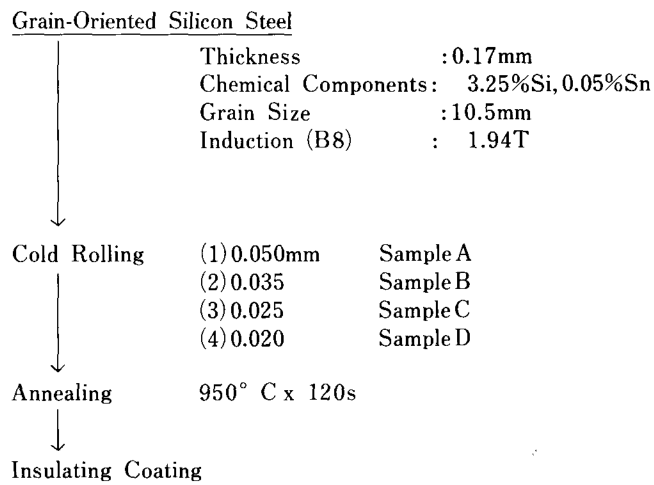


Fig. 1 Experimental procedure for the production of highly grain-oriented thin-gauge 3% Si-Fe

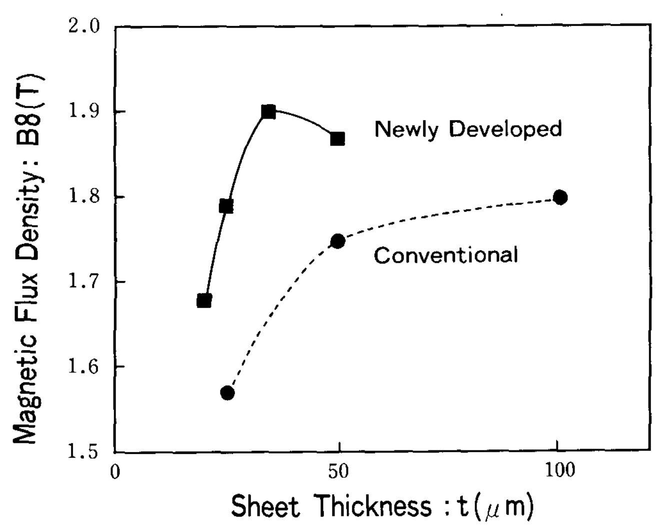


Fig. 2 Relationship between magnetic flux density (B8) and sheet thickness

Table 1 History of production of grain-oriented thin-gauge 3% Si-Fe in Japan

1949	M.F. Littmann invented the process (in the U.S.)
1950s	Yawata Steel Corp. started its production
1966	Nippon Kinzoku Co. Ltd started its production
1970	Yawata Steel Corp. and Fuji Steel Corp. merged into Nippon Steel Corp.
1970s	Nippon Steel transferred its production to Nippon Kinzoku Co. Ltd.
1994 (present)	Nippon Kinzoku Co. Ltd. is the only manufacturer

Table 2 Comparison fo standard values of JEM1239 and typical values of the products

Notation	Thickness, mm	Density, g/cm^3	Iron loss: W/kg W5/3000	W10/1000	W15/400	Induction (B8), T
Standarized values by JEM1239						
GT	0.025	7.65	≤35	...	...	≥1.52
	0.050	7.65	...	≤24	...	≥1.57
	0.10	7.65	...	...	≤15	≥1.77
Typical values of the products						
GT25	0.025	7.65	25.0	...	...	1.57
GT50	0.050	7.65	...	17.2	...	1.75
GT100	0.10	7.65	...	...	13.0	1.80

Table 3 Basic properties of the specimens

Sample	Thickness (t), μm	Induction (B8), T	Grain radius, μm
A	50	1.87	51
B	35	1.90	33
C	25	1.79	27
D	20	1.68	21

B8, higher than 1.85 T was developed by Nippon Steel Corporation (Ref 3, 4).

However, the magnetic properties of this material were not fully investigated. The purpose of this paper is to investigate physical parameters that affect core losses in view of excitation frequency and magnetic flux density and to clarify the features of this material.

2. Experimental

Figure 1 shows the experimental procedure for production of highly grain-oriented thin-gauge 3% Si-Fe. The starting material was grain-oriented 3% Si-Fe of 170 μm thickness. The sheet (3.3 mass% Si; 0.05 mass% Sn; magnetic flux density, B8 = 1.94 T; average grain diameter, D = 10.5 mm) was cold rolled to the four levels of thickness: 20, 25, 35, and 50 μm. These specimens were annealed at 950 °C for 120 s in a 25% N_2-75% H_2 atmosphere for primary recrystallization. After coating was applied for insulation, the specimens were wound to toroids and annealed at 800 °C for stress relief. Core losses were measured at the excitation magnetic flux densities of 0.5, 1.0, and 1.5 T in the frequency range of 0.1 to 20 kHz.

3. Results and Discussion

3.1 *Characterization of Highly Grain-Oriented Thin-Gauge 3% Si-Fe*

Figure 2 shows the relationship between magnetic flux density, B8, and sheet thickness of the products. The magnetic flux densities of the specimens are higher than those of the conventional products by more than 0.1 T.

The appropriate cold rolled reduction of tin-added specimen is 80%, which is 10% higher than that of the conventional material without tin-addition. This means that tin-addition is useful for producing a thinner product.

The crystal orientation was investigated by measuring {100} pole figures. Figure 3 shows the results. The main component is {110}⟨001⟩, and over the appropriate reduction, the {111} component emerges as a subcomponent. The latter component deteriorates the magnetic properties.

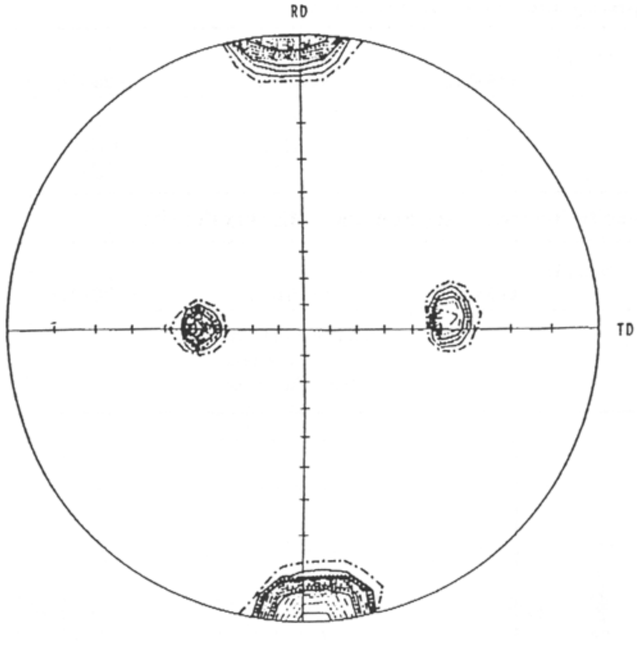
Figure 4 shows the grain structure of the sample A of 50 μm thickness. The specimen consists of the columnar grains. Figure 5 shows that the grain radius is closely related to the sheet thickness (Ref 5). In this experiment, the grain radius was proportional to the sheet thickness.

Table 3 summarizes the basic parameters of the four specimens prepared for the magnetic measurement.

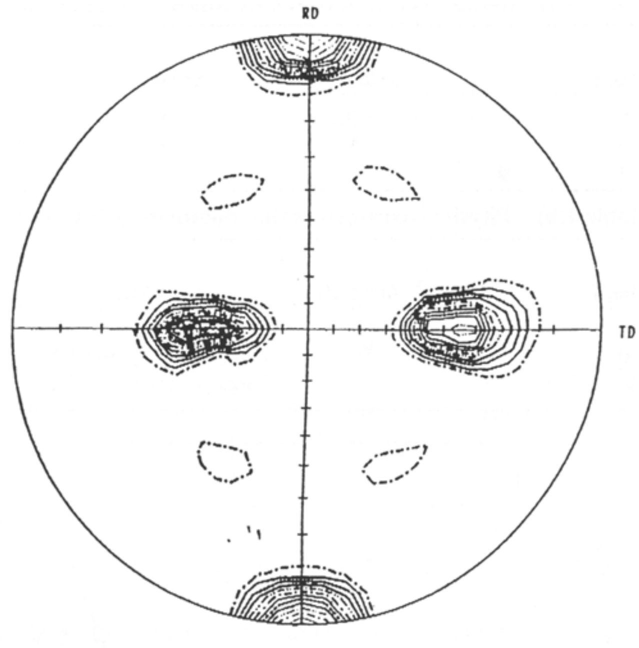
3.2 *Relationship between Core Losses and Excitation Conditions*

3.2.1 Core Loss at Bm = 0.5 T

Figure 6(a) shows the relationship between core loss per cycle and excitation frequency at excitation magnetic flux density of 0.5 T. The phenomenon is classified into two regions. The core losses increase drastically at 5 kHz. The linear increase of

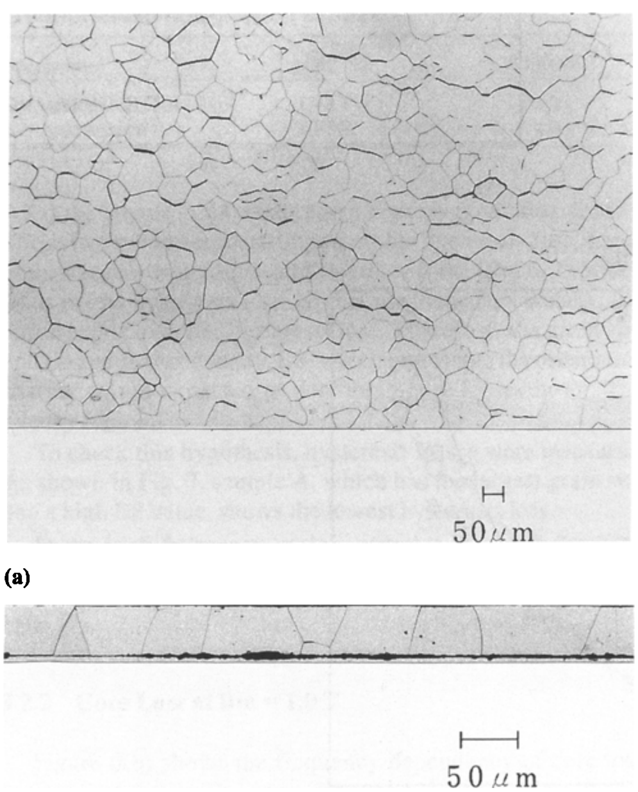


(a)



(b)

Fig. 3 {100} pole figures of highly grain-oriented thin-gauge 3% Si-Fe: (a) sample A (B8 = 1.87 T), (b) sample D (B8 = 1.68 T)



(a)

(b)

Fig. 4 Grain structure of grain-oriented thin-gauge 3% Si-Fe: (a) surface, (b) section

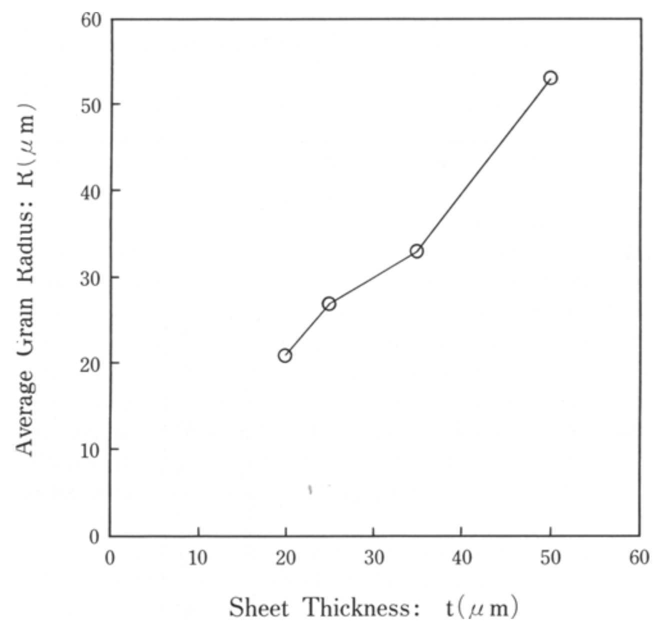


Fig. 5 Relationship between sheet thickness and grain radius

core loss per cycle up to 5 kHz suggests that the magnetization is achieved by simple 180° domain wall displacement. The rapid increase of core loss per cycle above 5 kHz reflects the change of magnetization process. Below 5 kHz, hysteresis loss takes a more important role. On the other hand, above 5 kHz, eddy-current loss dominates the phenomenon.

Among the four specimens, sample A shows the lowest core loss in the low frequency region. As shown in Table 3, sample

Table 4(a) Samples of the lowest core loss in view of excitation frequency and magnetic flux density

	Sample					
Bm, T	**At 0.1 kHz**	**At 0.4 kHz**	**At 1 kHz**	**At 5 kHz**	**At 10 kHz**	**At 20 kHz**
1.5	A (B)	B	B	C	C	C
1.0	A	A	...	C(D)	C(D)	C(D)
0.5	A	A	...	C(D)	C(D)	C(D)

Table 4(b) Physical parameters that dominate core loss in view of excitation frequency and magnetic flux density

	Sample					
Bm, T	**At 0.1 kHz**	**At 0.4 kHz**	**At 1 kHz**	**At 5 kHz**	**At 10 kHz**	**At 20 kHz**
1.5		High B8			High B8, thin thickness	
1.0		Large grain size, high B8			Thin thickness	
0.5		Large grain size, high B8			Thin thickness	

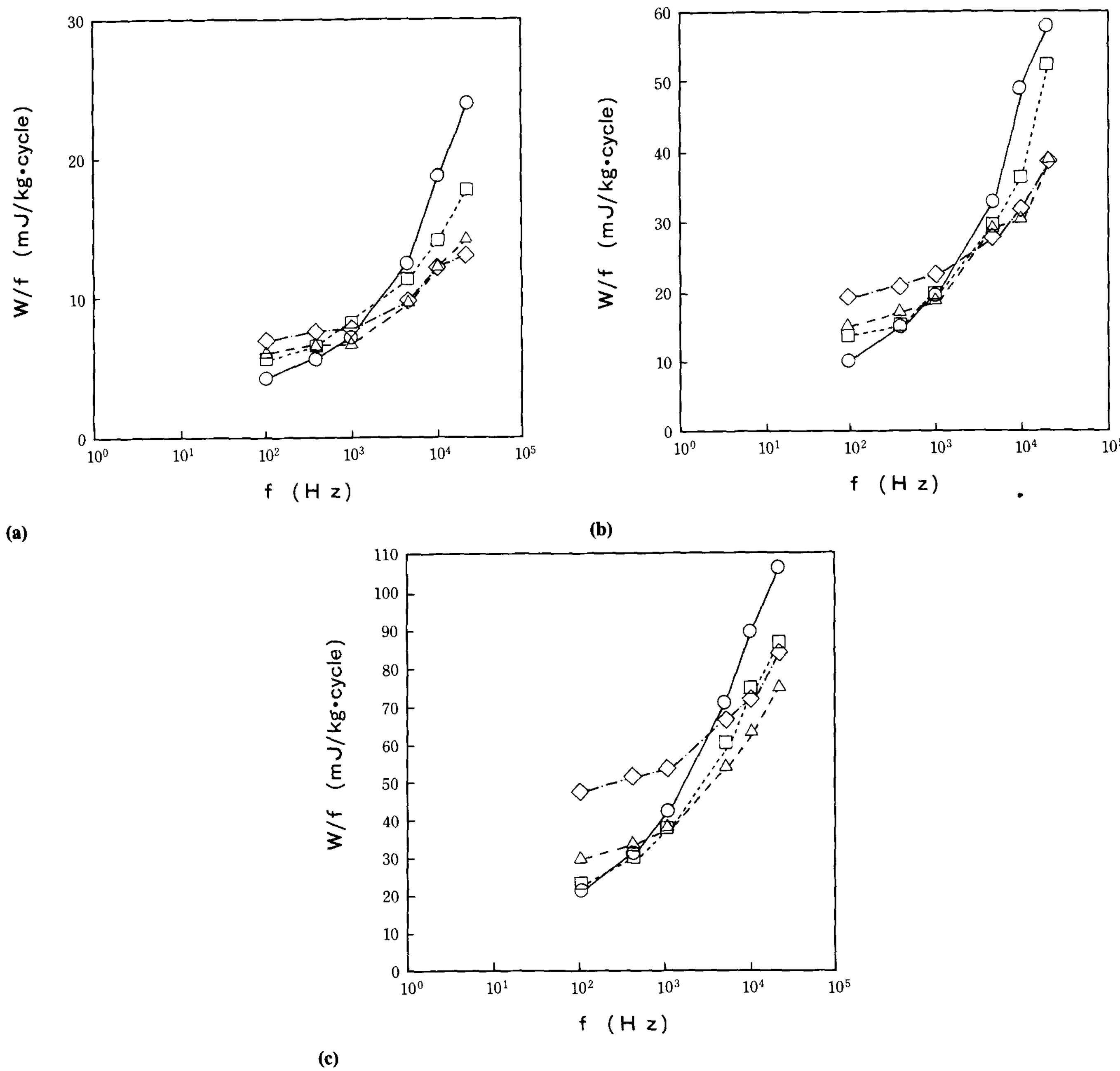


Fig. 6 Frequency dependency of core loss per cycle: (a) Bm = 0.5 T, (b) Bm = 1.0 T, (c) Bm = 1.5 T. ○: Sample A (50 μm, B8 = 1.87 T). □: Sample B (35 μm; B8 = 1.90 T). △: Sample C (25 μm; B8 = 1.79 T). ◇: Sample D (20 μm; B8 = 1.68 T).

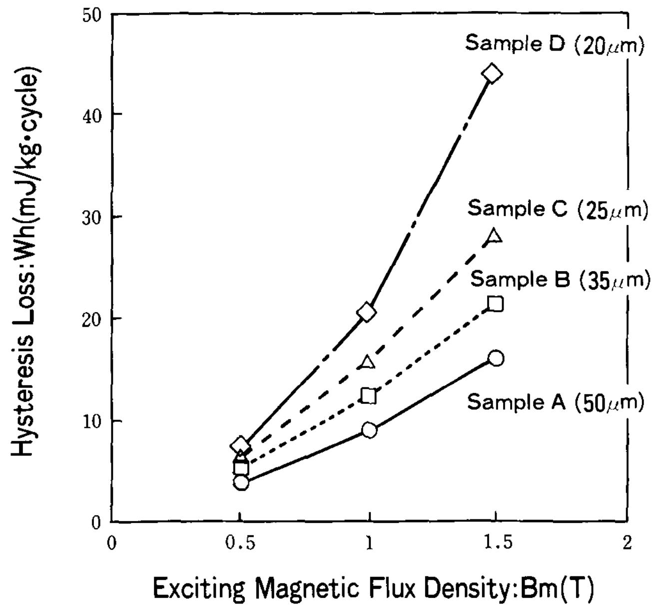


Fig. 7 Relationship between hysteresis loss of highly grain-oriented thin-gauge 3% Si-Fe and maximum excitation magnetic flux density

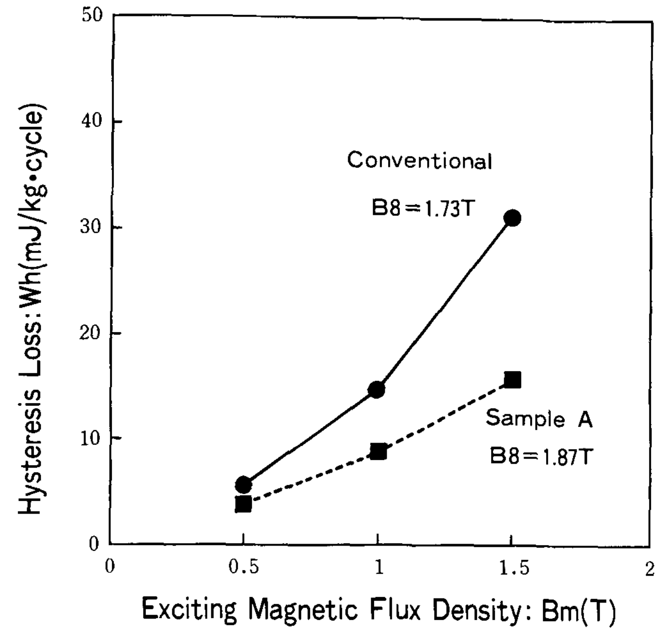


Fig. 8 Effect of magnetic flux density (B8) on the relationship between hysteresis loss and maximum excitation magnetic flux density (Bm)

Table 5 Core loss, W15/400, of the conventional and highly grain-oriented thin-gauge 3% Si-Fe

Specimen	B8	W15/400
Conventional (GT50)	1.73 T	14 w/kg
Newly developed	1.87 T	9 w/kg

A has the largest grain radius and a high magnetic flux density. These two parameters are important for hysteresis loss. Large grain size corresponds to small coercive force (Ref 6, 7), which leads to low hysteresis loss. Higher magnetic flux density, B8, corresponds to lower hysteresis loss. Therefore, the grain size and magnetic flux density, B8, which represents the orientation sharpness, are expected to determine core losses in this frequency region.

To check this hypothesis, hysteresis losses were measured. As shown in Fig. 7, sample A, which has the largest grain size and a high B8 value, shows the lowest hysteresis loss.

In the high frequency region, samples D and C show the lowest core loss. Therefore, the sheet thickness, which affects the eddy-current loss, dominates the phenomenon above 5 kHz.

3.2.2 Core Loss at Bm = 1.0 T

Figure 6(b) shows the frequency dependency of core loss per cycle at 1.0 T. The same features are observed as in Fig. 6(a). The phenomenon changes at 5 kHz. In the low frequency region, sample A, which has the largest grain size and a high B8 value, shows the lowest core loss. In the high frequency region, samples D and C have the lowest value, which means that sheet thickness dominates the phenomenon.

3.2.3 Core Loss at Bm = 1.5 T

Figure 6(c) shows the core loss per cycle at 1.5 T. In the low frequency region, sample B shows the lowest core loss. In the high frequency region, sample C shows the lowest core loss. This feature differs from those of the lower excitation magnetic flux densities of 0.5 and 1.0 T. In this high excitation magnetic density region, high magnetic flux density, B8, is the most important parameter.

Figure 8 shows the relationship between hysteresis losses and magnetic flux density of the two samples, Sample A and the conventional product of 50 μm thickness. The difference between the two samples is the difference of the B8 values. The B8 value affects hysteresis loss, especially at high excitation magnetic flux density. When excitation magnetic flux density approaches saturation magnetization, the magnetization process changes from simple 180° domain wall movement to annihilation and creation of supplementary domains. Because the latter process needs larger energy, hysteresis loss deteriorates drastically.

At the high frequency region, core loss depends not only on B8 value but also on sheet thickness. Therefore, sample C shows the lowest value.

3.2.4 Core Loss Summary

Tables 4(a) and (b) summarize the core loss results. In Table 4(a), the sample with the lowest core loss among the four samples is selected in each excitation magnetic flux density, Bm of 0.5 to 1.5 T, and frequency, of 0.1 to 20 kHz. Frequency dependency loss is divided into four categories by the dotted lines. Frequency dependency loss is recapitulated by physical parameters that dominate core loss, as shown in Table 4(b).

In the frequency region lower than 5 kHz, hysteresis loss is more important than eddy-current loss. Grain size and B8 value are important parameters in this region. in the high frequency region, eddy-current loss predominates, and sheet thickness becomes the important parameter.

At higher excitation magnetic flux density, where magnetization process changes from 180° wall displacement to annihilation followed by creation of supplementary domains, core loss deteriorates drastically. Therefore, sharpness of {110}⟨001⟩ orientation distribution, which is represented by the B8 value, is the most important parameter.

As a summary of the investigation, highly grain-oriented thin-gauge 3% Si-Fe has the advantage at high excitation magnetic flux density (Bm > 1.0T) in the middle frequency range (0.1 to 1 kHz).

Table 5 shows an example of the core loss of 400 Hz at 1.5 T. The core losses of the conventional and the newly developed thin-gauge 3% Si-Fe are 14 and 9 w/kg, respectively; that is, core loss could be improved by 30% by controlling the sharpness of {110}⟨001⟩ orientation.

4. Conclusions

Physical parameters that affect core losses were investigated in view of excitation frequency and magnetic flux density with recently developed highly grain-oriented thin-gauge 3% Si-Fe.

The relationship between core loss and excitation conditions is classified into four regions. In view of frequency, dominant loss component changes drastically at 5 kHz. Physical parameters that affect hysteresis loss, magnetic flux density (B8) and grain size, dominate the core loss below 5 kHz. Physical parameters that affect eddy-current loss, sheet thickness, dominate the core loss above 5 kHz.

In view of excitation magnetic flux density, magnetization process changes in the region of 1.0 to 1.5 T. Magnetic flux density, B8, becomes more important as excitation magnetic flux density increases.

The newly developed material was useful for transformers and inductors, especially for high design flux density (Bm > 1 T) in the middle frequency region (10^2 to 10^3 Hz).

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