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1 Introduction

There is a growing demand for the grain-oriented electrical steel used as the material for transformer cores to have reduced levels of iron loss in order to achieve ever greater energy savings. As a result, steel manufacturers have been concentrating their efforts on finding ways to reduce iron loss in steel sheets. Efforts to reduce iron loss in grain-oriented electrical steel were pursued mainly through reductions in hysteresis loss achieved by improving the orientation of crystals. Hysteresis loss was dramatically improved through the development of high flux density grain-oriented electrical steel.[1,2] Due to a reduction in hysteresis loss, eddy current loss came to some 70% of the iron loss occurring in grain-oriented electrical steel. The aim of research and development has also been shifted to the finding of effective ways of reducing eddy current loss.

Eddy current loss has been reduced through a variety of means such as raising electric resistivity through an increase in silicon content, by reducing the grain size, as well as by making the thickness of the steel sheet thinner.[3] Another technique aimed at controlling magnetic domain structure in addition to these various metallurgical methods was also developed in order to reduce eddy current loss. This technique consists of artificially reducing the width of the 180° domain. In particular, the method to refine magnetic domains through an irradiation of laser beam[4] or plasma flame[3,5,6] on secondary recrystallized steel sheet was industrialized, thereby making it possible to produce epoch-making materials having low iron loss. The iron loss of transformers has thus been markedly reduced by virtue of the development of magnetic domain controlled materials. These materials have come to be widely used particularly in foreign countries where loss evaluation systems[3] have been established. However, one drawback of this type of material is that the iron loss of magnetic domain controlled materials irradiated with laser beams, plasma flames and the like deteriorate when the material is annealed at high temperatures. Therefore, these materials could not be used for wound core transformers which need to be annealed in order to minimize strain. For this reason, it was subsequently considered desirable to develop heat-proof domain-refining techniques in order to make it possible to use these types of materials for wound core transformers, as well.

Responding to this need at that time, Kawasaki Steel went ahead with research and developed a new type of domain-refined grain-oriented electrical steel, referred to as RGHPD, in 1992 which is capable of enduring stress-relief annealing[7,8] The technique developed con-

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sists of introducing linear grooves onto the surface of the steel after final cold rolling through the application of localized electrolytic etching so as to refine magnetic domains through the demagnetizing field effect.

This paper outlines this newly developed heat-proof domain-refining technique and describes examples of its application in materials used for transformers.

2 Mechanism of Domain Refining through the Introduction of Linear Grooves

2.1 Magnetic Domain Refining of Grain-Oriented Electrical Steel

Magnetization of grain-oriented electrical steel is primarily accompanied by the domain wall motion of 180° magnetic domains and the eddy current caused by the domain wall motion brings about losses. Pry and Bean found that eddy current loss can be approximately expressed according to the following equation.[9)]

$$P = 1.63P_{ce}(2L/d) \quad \text{(erg/g)}$$

where

P_{ce}: Classical eddy current loss, $P_{ce} = (\pi d B_m f)^2/6\rho$
d: Sheet thickness (cm)
B_m: Maximum magnetic flux density (G)
f: Frequency (Hz)
ρ: Electric resistivity ($\Omega \cdot$ cm)
L: Width of 180° magnetic domain (cm)

It can be seen from this equation that reducing the width of the 180° magnetic domain is effective in reducing eddy current loss.

As can be seen in **Fig. 1**, iron loss in grain-oriented electrical steel sheets generally tends to decrease as the magnetic flux density (B_8) becomes higher. However, it tends to increase somewhat when the magnetic flux increases beyond a certain limit. The reason for this is because crystal grain size tends to increase and the width of the 180° magnetic domain becomes larger, although hysteresis loss decreases due to an improved orientation of crystals which in turn leads to an increase in eddy current loss. As a result, as shown in Fig. 1, it becomes possible to obtain materials with remarkably low iron loss by reducing eddy current loss through a refinement of the 180° magnetic domain width. In this case, the iron loss after magnetic domain refinement becomes more dependent on hysteresis loss. Consequently, the higher the magnetic flux density of a material is, the lower the iron loss becomes.

The method of locally introducing grooves and utilizing the demagnetizing field effect resulting from the magnetic poles generated in the vicinity of these grooves is effective as a technique for artificially refined 180° magnetic domains endurable to stress relief annealing at high temperatures. Although magnetic poles can also be generated by forming fine particles of foreign material instead of grooves, the quantity of magnetic poles thus generated becomes small when these materials are not non-magnetic. Thus, the introduction of grooves is considered to be the most suitable means of generating magnetic poles on the material.

When introducing grooves onto the material surface, the shape of the grooves is important in taking full advantage of the demagnetizing field effect. Thus, the relationship between the shape of the grooves and the resulting effect on domain refining was examined with calculations using magnetic domain model[10)] as the next step in this research.

2.2 Shape of Grooves and Domain Refining Effect

Let us consider a case in which linear grooves having a rectangular shape are formed perpendicularly to the rolling direction on the surface of a steel sheet having an axis of easy magnetization in the rolling direction as shown in **Fig. 2**. In the structural model of the magnetic domains, the 180° domain walls are assumed to be parallel to the direction of rolling and perpendicular to the

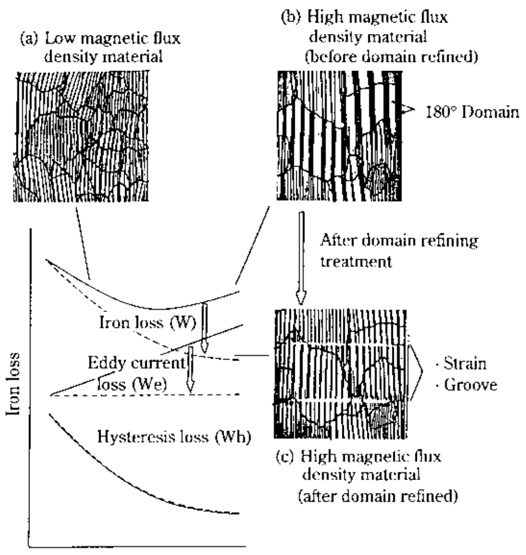

Fig. 1 Iron loss and domain structures of grain-oriented electrical steel sheets

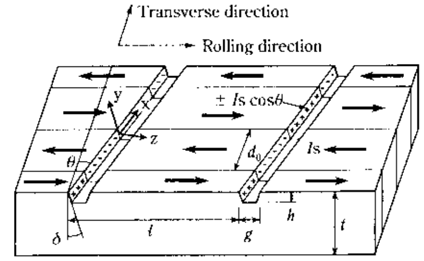

Fig. 2 Model of 180° domain walls occuring in a grooved grain-oriented silicon steel sheet used for the present analysis

surface of the sheet.

Magnetic poles are generated on the groove sections as indicated by + and − signs in the figure. These magnetic poles bring about an increase in magnetostatic energy. As a result, the width of the 180° magnetic domain must be decreased in order to reduce the amount of magnetostatic energy present. Although magnetostatic energy decreases as the width of the 180° magnetic domain is reduced, domain wall energy increases. Therefore, the domain structure is determined in such a way as to minimize the sum of magnetostatic energy and domain wall energy.

In actual analysis, the magnetic potential is obtained first on the basis of the magnetic poles generated by the formation of the grooves accoding to Kittel's method, and then, magnetostatic energy is calculated. As mentioned above, although magnetostatic energy decreases as domain width decreases, the consequent increase in the number of domain walls resulting from the narrower domain width results in a corresponding increase in domain wall energy. Since the domain width is determined such that the sum of magnetostatic energy and domain wall energy is minimized, the domain width is determined analytically by obtaining the condition of such a case. When the grooves are tilted, the μ^* effect is considered to become influential, which is known as an effect that the magnetostatic energy is lowered by bypathing of the magnetic flux around the tilted side walls and that the generation of magnetic poles is avoided. For this reason, calculations were made taking the μ^* effect into account. Although the details of the calculations are omitted here in this paper, the results obtained are described below.

The stable domain width d_0 is given by

$$d_0 = \begin{cases} \dfrac{2\pi\mu_0(1 + I_s^2 \sin^2 \delta/4\mu_0 K_1)\gamma t l}{I_s^2 h \cos\theta} & (h \ll d_0) \\ \sqrt{\dfrac{2\pi\mu_0(1 + I_s^2 \sin^2 \delta/4\mu_0 K_1)\gamma t l}{0.853 I_s^2 h \cos\delta}} & (h \gg d_0) \end{cases}$$

where

- g: Width of grooves
- h: Depth of grooves
- l: Pitch of grooves
- δ: Tilt angle of side walls of grooves from the direction vertical to the sheet surface
- θ: Introduction angle of grooves from the direction transverse to the rolling direction
- t: Thickness of steel sheet
- I_s: Spontaneous magnetization
- γ: Domain wall energy per unit area
- K_1: Crystal anisotropy constant in cubic crystal
- μ_0: Magnetic permaeability in a vacuum

Figure 3 shows the results of calculations when $l = 3$ mm, $\theta = 10°$ and $\delta = 20°$. The figure indicates that the domain width d_0 tends to become smaller as the groove depth h gets larger. Measured values of the domain width are plotted in the figure. These values are in a good agreement with the results of calculation.

Using the domain width calculated according to the model described above, eddy current loss was calculated taking Pry and Bean's equation[9] and the equation for in-plane eddy current loss proposed by Yamaguchi[11] into consideration. These calculated values for eddy current loss were then compared with the eddy current loss and other magnetic properties actually measured for grain-oriented electrical steel sheet having various linear grooves. **Figures 4** and **5** show the changes in magnetic properties when the groove width and groove pitch are changed, respectively. Although the calculated values and measured values for eddy current loss differ from each other to some extent, this is presumably due to the reason that single crystals were assumed in the model used for the calculations, while the actual materials are polycrystalline. Consequently, the actual domain width varies for respective crystal grains and changes as a result of the effects of adjacent crystal grains. However, it can be seen that the behavior of eddy current loss corresponding to changes in the groove shape can be qualitatively explained by the model calculations.

As groove depth becomes larger and groove pitch becomes smaller, eddy current loss decreases. On the other hand, hysteresis loss tends to increase. Therefore, there exist optimum values for groove depth and pitch. It can be seen from Figs. 4 and 5 that the optimum values for groove depth and pitch are about 20 μm and 3 mm, respectively. **Figure 6** shows the relation between the tilt angle of a groove side wall δ, and the domain width d_0. From this figure, it can be seen that the tilt angle of grooves must be reduced as much as possible, that is, the shape of the grooves must be as close to being rectangular as possible, in order to make the domain width as small as possible.

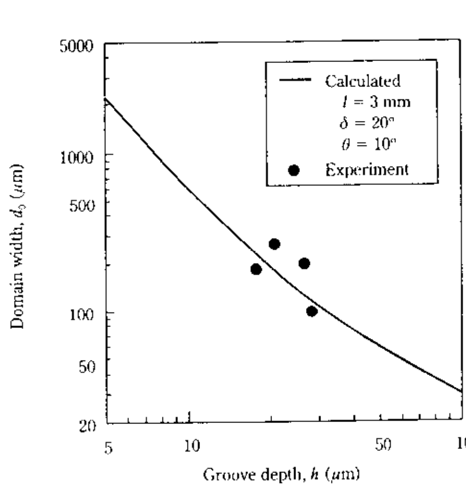

Fig. 3 Dependence of the stable domain width on groove depth

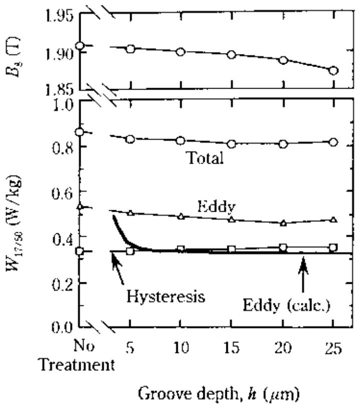

Fig. 4 Dependence of magnetic flux density B_8 and iron loss $W_{17/50}$ on the groove deptth (the solid line, calculated; the symbols, measured in 0.23 mm thick Epstein specimens)

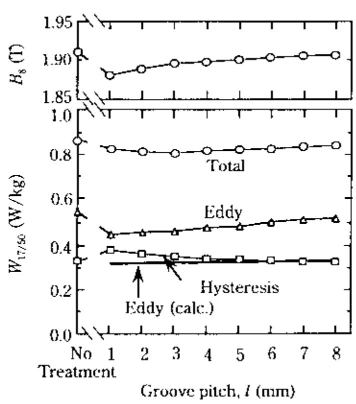

Fig. 5 Dependence of magnetic flux density B_8 and iron loss $W_{17/50}$ on the groove pitch (the solid line, calculated; the symbols, measured in 0.23 mm thick Epstein specimens)

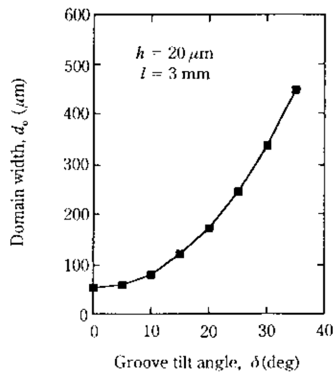

Fig. 6 Stable domain width calculated with μ^* effect against groove wall tilt angle δ

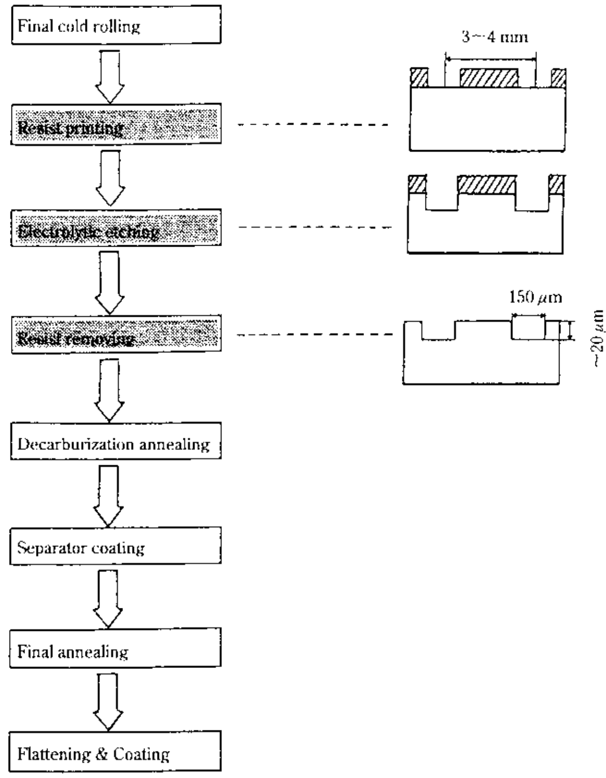

Fig. 7 Newly developed process for grooving

3 Newly Developed Heat-Proof Domain-Refining Technique

3.1 Process and Special Features

Since the introduction of linear grooves is effective as a heat-proof domain-refining technique, as explained in the preceding section, it is essential to sellect approriately the shape of the grooves in order to attain the full extent of the magnetic domain refining effect.

From this viewpoint, Kawasaki Steel investigated the matter in order to determine its practical potential for industrialization and developed new techniques. **Figure 7** shows the newly develped process for grooving. The shadowed parts in the figure indicate the techniques which were newly developed. Etching resistant ink is printed over the steel after final cold rolling in a stripe shape perpendicularly to the rolling direction leaving unpainted parts. The steel sheet is then electrolytically etched to form grooves at the exposed, unpainted parts of the steel. The grooves are made with a width of about 200 μm, a depth of about 20 μm, and a pitch in the rolling direction of 3–4 mm. After the etching resistant ink is then removed by immersing the steel sheet into an alkaline solution, the steel sheet is subjected to the ordinary processes of decarburization annealing, final annealing, insulation coating, and flattening.

The advantages of applying this type of grooving treatment to final cold rolled sheets are as follows.

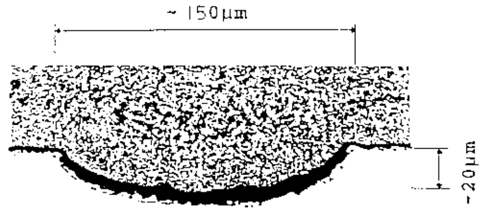

Photo 1 Cross-sectional view of the grooved region of a steel surface after final annealing

(1) An insulating film is formed in the grooved region as well through decarburization annealing and final annealing. As a result, the grooves do not affect the insulation performance of the product at all (**Photo 1**).
(2) The product is free from residual strain. Consequently, it can be used not only for wound core transformers but also for stacked core transformers.

3.2 Magnetic Properties of Etching Treated Material

Steel sheets were produced by means of the newly developed method described briefly above. The magnetic properties of these sheets after stress relief annealing are shown in **Fig. 8** as compared with the magnetic properties of materials without grooves. According to the figure, it is found that the iron loss is reduced by 10–15% as a result of grooving. Similar to the case of plasma flame irradiation, the large effect of iron loss reduction is attained with an increase in the magnetic flux density of a material.

One point in which this technique differs from the case of plasma flame irradiation is that the B_8 value decreases by 0.02–0.03 T in the case of groove introduction. However, the decrease in B_8 in this case is not caused by changes in the texture of the material but is caused by a decrease in saturation flux density due to the existence of the grooves themselves. Therefore, as shown in **Fig. 9**, the magnetic permeability of material

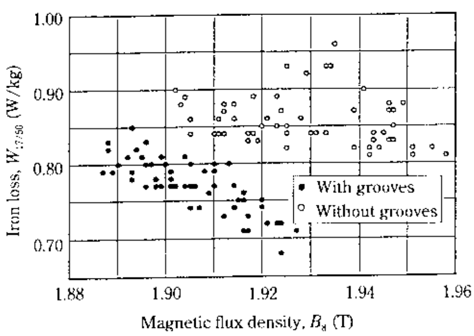

Fig. 8 Iron loss of steel sheets with and without grooves (0.23 mm in thickness)

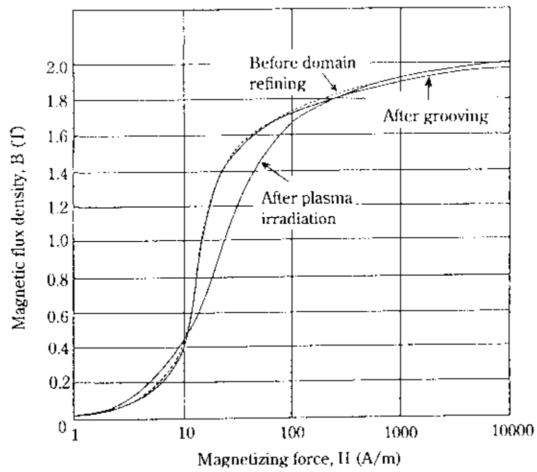

Fig. 9 DC magnetization curves before and after grooving and plasma irradiation

with grooves is nearly the same as that of material without grooves in a range of magnetic flux density of less than 1.7 T. Figure 9 also shows the magnetization curve of material irradiated by plasma flame. Here the magnetization properties of the material deteriorates in low magnetic fields in cases where the materials are irradiated by plasma flames and laser beams. From the above, it is considered that the decrease in B_8 values of grooved materials does not cause any problem for practical use. Further, grooving is somewhat more advantageous compared with plasma flame or laser beam irradiation in the sense of magnetization properties and noise properties.

The magnetostriction curves of the materials with and without grooves are shown in **Fig. 10**. There are only minor differences between these two materials with respect to both magnetization properties and compressive stress properties. It may also be said that there are only minor changes in magnetostriction properties as a result of grooving. **Figure 11** shows the results of spectral analysis of magnetostrictive oscillation for grooved, ungrooved, and plasma flame irradiated materials. From this figure, it is understood that the harmonic component of magnetostriction, which is considered as a major cause of noise, is smaller in the case of grooved materials than in the case of plasma flame irradiated materials. Thus, grooved materials have superior noise properties.

3.3 Domain Structure of Grooved Materials

The domain structure of grooved materials as compared with that of plasma flame irradiated materials and ungrooved materials is shown in **Photo 2**. The photograph shows that the domain width is smaller in the case of both grooved and plasma flame irradiated materials than in the case of ungrooved material. However, the detailed observation indicates that there are differences in the domain structures between grooved and plasma

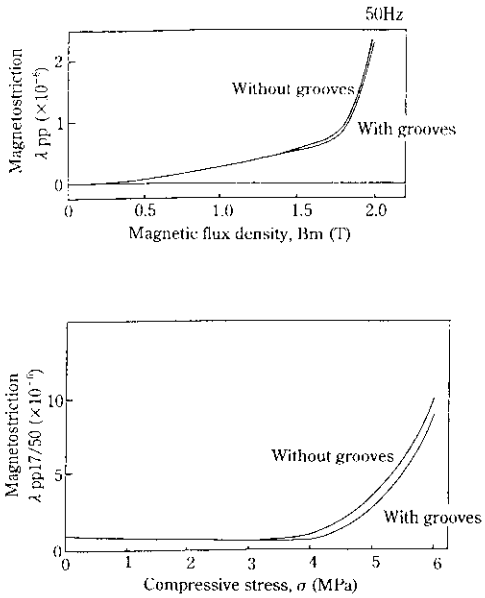

Fig. 10 Magnetostriction curves of materials with and without grooves

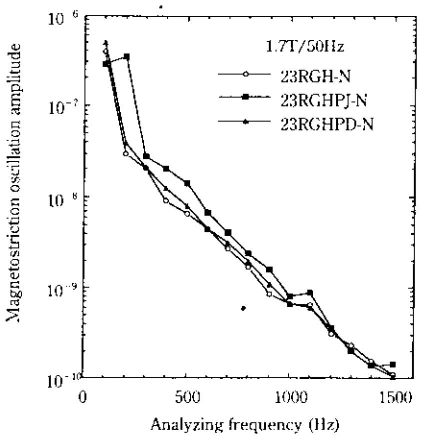

Fig. 11 Spectral analysis of magnetostriction oscillation

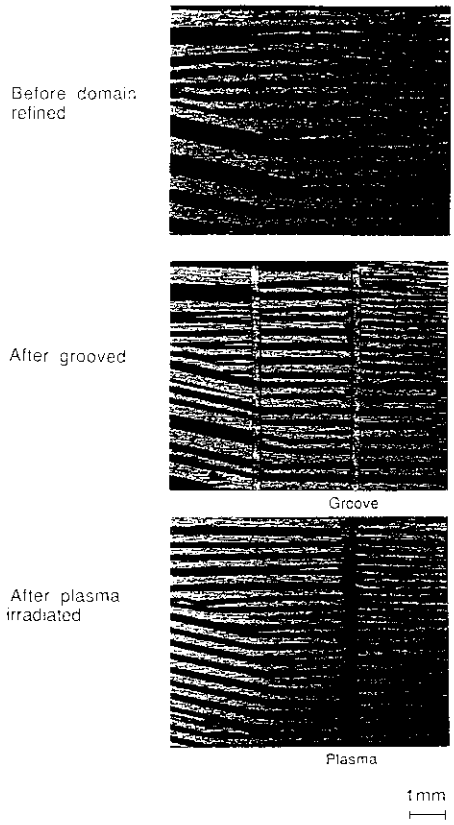

Photo 2 Domain patterns before and after grooving or plasma irradiation

flame irradiated materials and ungrooved one. **Photo 3** shows the domain structures of the treated, cross-sectional and untreated surfaces of these materials during the process of DC magnetization. In the demagnetized condition A, 180° magnetic domains are observed in the cross-section. Further, no inhomogenity in the domain structure is found at those areas where grooves have been introduced, in the case of grooved material. However, stress patterns (90° magnetic domains) are sbserved at irradiated areas, with the effects penetrating to the bottom surface in the case of plasma flame irradiated material. When these materials are magnetized by DC the grooved material tends to have delays in magnetization on the grooved surface side due to the existence of grooves up to about 1.7 T (condition C), while the ungrooved surface side becomes promptly magnetized to that extent. Therefore, no delay in magnetization occurs with grooved materials as a whole. In addition, the magnetization properties of grooved materials are considered not to differ from those of ungrooved (untreated) materials up to about 1.7 T. At about 1.7 T, the magnetic flux density on the ungrooved surface side becomes saturated, and magnetization hardly progresses beyond 1.7 T. As a result, the saturated magnetic flux density becomes lower than that for ungrooved materials. On the other hand, in the case of plasma flame irradiated materials, magnetization tends to be delayed both on the top surface and bottom surface in lower magnetic fields (condition B) due to the existence of 90° magnetic domains reaching to the bottom surface at irradiated areas. This corresponds to a deterioration in magnetization properties in the range below 1.7 T. However, 90° magnetic domains disappear with the application of a stronger external magnetic field, while plasma flame irradiated materials reach an equivalent state of magnetization saturation as ungrooved materials.

As explained above, although the level of magnetization saturation tends to become low in the case of grooved materials, any differences can hardly be

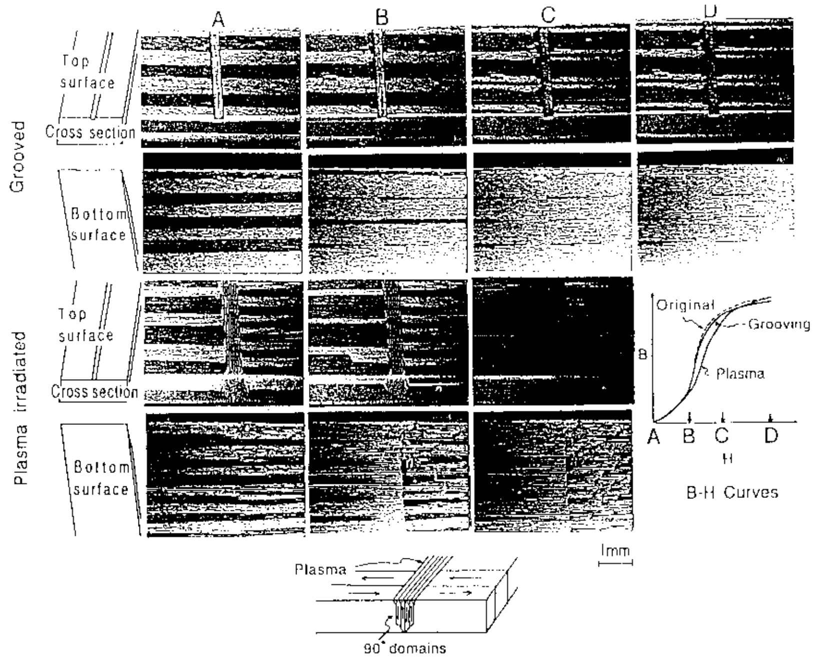

Photo 3 Change in the domain structure during DC magnetization

detected in magnetic properties up to about 1.7 T which is considered important from the viewpoint of practical application.

4 Properties of Transformers Made of Grooved Material

4.1 Properties of Wound Core Transformers

A wound core having a capacity of 20 kVA was produced as a part of the study, as shown in **Photo 4**, and the magnetic properties of wound core transformers made of the grooved material were evaluated. The results of the measurement made are shown in **Tabel 1**. In the table, the results obtained from transformers made of an ungrooved material are also included for comparison. The building factors of the cores (B.F. = transformer core's iron loss/material's iron loss) are equivalent, being about 1.0 for both, which means that the magnetic properties of the core materials are reflected in those of the transformers. Noise was measured at four positions 300 mm apart from the cores and at a height of 1/2 of the core. The average values for measured noise

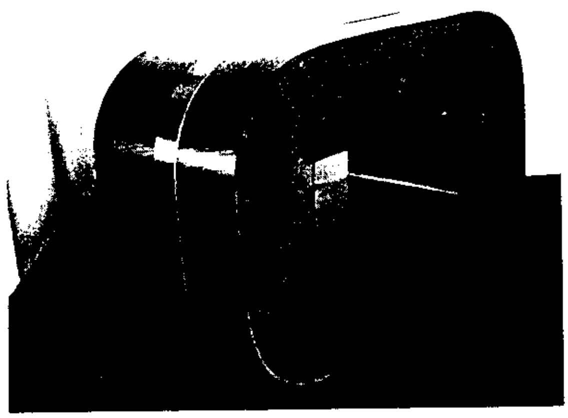

Photo 4 Photograph of a step-lap wound-core made with newly developed materials (capacity: 20 KVA, weight: ~50 kg)

Table 1 Magnetic properties of wound-core transformers (0.23 mm in thickness)

Materials	Magnetic properties of sheets			Magnetic properties of transformer cores			Building factor (B.F.)	
	B_8 (T)	$W_{17/50}$ (W/kg)	$W_{15/60}$ (W/lb)	$W_{17/50}$ (W/kg)	$W_{15/60}$ (W/lb)	$Noise_{17/50}$ (dB)	$W_{17/50}$	$W_{15/60}$
With grooves	1.90	0.782	0.343	0.793	0.339	43	1.01	0.99
Without grooves	1.93	0.892	0.389	0.911	0.384	42	1.02	0.99

$$B.F. = \frac{\text{Iron loss of transformer cores}}{\text{Iron loss of materials}}$$

Table 2 Magnetic properties of stacked-core model transformers

Sheets grade	Magnetic properties of sheets		Magnetic properties of model transformer cores			
	B_8 (T)	$W_{17/50}$ (W/kg)	$W_{17/50}$ (W/kg)	$VA_{17/50}$ (VA/kg)	$Noise_{17/50}$ (dB)	B.F.
23RGHPD	1.90	0.78	0.90	2.3	52	1.15
23RGHPJ	1.93	0.78	0.90	2.9	55	1.15

are shown in the table. The value for background noise at measurement was 24 dB.

4.2 Properties of Stacked Core Transformers

The results obtained from a stacked core model transformer made of the grooved material (RGHPD) are shown in **Table 2** and are compared with the results obtained from a transformer made of plasma flame irradiated material (RGHPJ). The joining geometry is a step-lap with a two-part V-shaped notch as shown in **Fig. 12**. The building factors of the transformer core are almost identical for both RGHPD and RGHPJ. On the other hand, the levels of excitation VA and noise are slightly lower for RGHPD which corresponds to the results expected from the properties of the materials described in the preceding section.

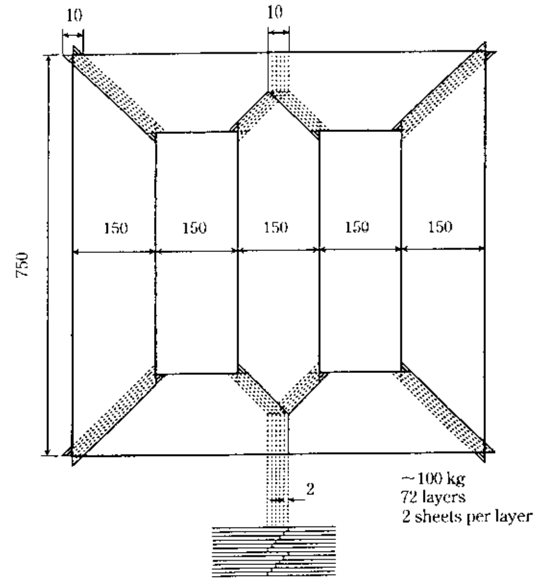

Fig. 12 Stacked core structure for model transformer (step-lap joint)

5 Conclusion

Kawasaki Steel has developed a new heat-proof domain-refining technique for locally forming linear grooves on final cold rolled sheets of grain-oriented electrical steel by electrolytic etching.

The special features of the newly developed material are summarized below.

(1) Iron loss has been reduced by about 10% compared with steel sheets which have not undergone grooving treatment, and its effect is not changed by stress relief annealing.

(2) The magnetic flux density B_8 decreases by 0.02–0.03 T as a result of the grooving treatment, however, the magnetization properties of the material barely change up to a level of 1.7 T.

(3) The magnetostriction properties of the grooved material are superior to those of plasma flame irradiated materials.

(4) As a result of using this new material for wound core transformers, a reduction of iron loss of about 10% was attained.

(5) As a result of using this new material for stacked core transformers, it was found that the building factor is equivalent to transformers made of plasma flame irradiated material, and that noise becomes lower for grooved material as compared with plasma flame irradiated material.

As described above, it is clear that the newly developed grooved material can be used for transformers regardless of whether it is with stacked cores or wound cores. The use of this material can also be expected to contribute significantly towards the achievement of greater energy-savings from now on through the improvement of transformer efficiency.

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