KAWASAKI STEEL TECHNICAL REPORT

No.22 (May 1990)

Advanced Technologies of Iron and Steel,

Commemorating the 20th Anniversary

of the Technical Research Division

Developments of Grain-Oriented Silicon Steel Sheets with Low Iron Loss

Toshio Sadayori, Yoshiaki Iida, Bunjiro Fukuda, Katsuo Iwamoto, Keiji Sato, Yo Shimizu

Synopsis :

Two approaches for reducing iron losses in grain oriented Si-steel sheets were described. One is a metallurgical approach with reduces sheet thickness, increases Si content, and optimizes grain diameter without deteriorating texture orientation. Increase in C content, hot rolling at low temperature and low speed, and utilization of very fine carbides have been applied for that purpose. The other is a physical approach and is called the "domain refining technique". Plasma-jet (PJ) irradiation has been found to be effective for refining domain wall spacing without deteriorating surface coatings of sheets. PJ irradiation has enabled further loss reduction in thin gauge grain-oriented Si-steel sheets.

The body can be viewed from the next page.

Developments of Grain-Oriented Silicon Steel Sheets with Low Iron Loss*


Toshio Sadayori
General Manager, Electrical Steel Research Dept., Iron & Steel Res. Labs.


Yoshiaki Iida
Staff Assistant General Manager, Silicon Steel & Coated Products Dept., Hanshin Works.


Bunjiro Fukuda
Senior Researcher, Electrical Steel Research Dept., Iron & Steel Res. Labs.


Katsuo Iwamoto
Senior Researcher, Electrical Steel Research Dept., Iron & Steel Res. Labs.


Keiji Sato
Senior Researcher, Electrical Steel Research Dept., Iron & Steel Res. Labs.


Yo Shimizu
Staff General Manager, Electrical Steel Control Sec., Mizushima Works

Synopsis:

Two approaches for reducing iron losses in grain oriented Si-steel sheets were described. One is a metallurgical approach which reduces sheet thickness, increases Si content, and optimizes grain diameter without deteriorating texture orientation. Increase in C content, hot rolling at low temperature and low speed, and utilization of very fine carbides have been applied for that purpose.

The other is a physical approach and is called the "domain refining technique". Plasma-jet (PJ) irradiation has been found to be effective for refining domain wall spacing without deteriorating surface coatings of sheets. PJ irradiation has enabled further loss reduction in thin gauge grain-oriented Si-steel sheets.

1 Introduction

Today we depend so heavily on electricity that much of modern life would be unthinkable without it. This essential part of our lives is supplied through a power system which includes generators and transformers. The core of the transformer is composed of grain-oriented silicon steel sheets. Greater demand for electric power has meant an increased need for transformers and hence increased demand for grain oriented silicon steels. In 1987, 570 000 transformers[1] and well over 300 000 t of grain-oriented silicon steel were manufactured in Japan.

The most important requirement placed on the grain-oriented silicon steels used as transformer cores is for low iron loss. Iron loss is the heat energy loss generated in the steel material while the transformer is in use. In Japan, approximately 6% of all electrical power generated annually is lost in the power transportation system. Transformer iron loss accounts for about 18%. In other terms, iron loss costs Japan alone some 6.5 billion kWh, or about 100 billion yen (at ¥15/kWh) each year.[2,3] Following the two oil crises of the 1970s, the need for energy conservation became urgent, giving strong impetus to the adoption of low iron loss transformers, and as a result, a loss evaluation system for calculating the monetary cost of power losses became firmly established, especially outside Japan.

In the loss evaluation system, iron loss and copper loss (Joule loss of the copper winding) in the tansformer are expressed respectively as monetary values and added to the price of the transformer to obtain a "total owning cost," which is taken as the evaluation of the transformer. The use of sheets with better iron loss than that of conventional materials in a transformer reduces the total owning cost of the unit and gives it a competitive advantage, provided the monetary savings realized by the improved performance of the sheets outweigh the increased material cost. Depending on supply and demand conditions affecting electricity, interest rates, and other factors, the loss evaluation system shows that the cost of iron loss can range from 100 000

* Originally published in *Kawasaki Steel Giho*, 21(1989)3, pp. 239-244

yen to 3 million yen per kilowatt. Because copper loss occurs only under conditions of loading, the loss evaluation for copper depends on the ratio of loading; it is, however, on the order of 2/3 to 1/5 that for iron loss.

With growing application of loss evaluation system, the demand for better iron loss performance based on the use of grain oriented silicon steels has become increasingly strong, prompting steelmakers to an active, ongoing pursuit of lower iron loss products. This paper describes trends in lower iron loss steel sheets and discusses the development of the world's highest grade thin grain-oriented silicon steel and of domain-refined grain-oriented silicon steel sheets.

2 History of Low Iron Loss Technology

The outstanding magnetic properties of silicon steel were first observed in 1900 by R.A. Hadfield. Within a few years, silicon steel was being produced industrially in the United States and Germany in the form of hot-rolled silicon steel sheets, and had found use in transformers. Its first production in Japan was in 1924 at Yawata Steel and in 1931 at the sheet factory of Kawasaki Dockyard, Ltd., the predecessor firm to the present-day Kawasaki Steel Corp.[4)] With hot-rolled sheets, the principal means of reducing iron loss were higher Si contents, reduction of impurity levels, and the prevention of oxidation and nitrization.

In 1934, grain-oriented silicon steel was invented by N.P. Goss. Improvement of manufacturing techniques continued in the United States into the 1950, when substantial completion of this technology was achieved. In Japan, concerted efforts were also made from the Second World War into the postwar era, mainly by the Institute of Electrical Engineers of Japan with the cooperation of specialists in academic and industrial circles, but Japanese makers failed to achieve the same results as their American counterparts. In 1958, however, Yawata Steel introduced technology from Armco, leading to a rapid improvement in product quality.[5)] Kawasaki Steel pursued an independent course, and in 1959 began the commercial production and sale of grain-oriented silicon steel sheets (RG).[6)]

The year 1968 marked a turning point. Leadership in the field of silicon steel sheet production technology passed from the U.S. to Japan when Nippon Steel Corporation (of which Yawata Steel was one of two predecessor firms) marketed a highly grain-oriented silicon steel sheet product (Hi-B), based on an enhanced crystal orientation.[7)] Kawasaki Steel developed a highly grain oriented silicon steel sheet (RGH) in 1973.[8)] In this connection, it is noteworthy that all highly grain-oriented silicon steel sheet products now in use worldwide are of either the Hi-B type or the RGH type.

Highly grain-oriented silicon steel sheet made possible a reduction of approximately 10% in iron loss through a reduction in hysteresis loss obtained by improvement of crystal orientation. With this reduction in hysteresis loss, eddy current loss, which had accounted for about 60% of iron loss, became proportionally more important, now accounting for 70% (for 0.30-mm-thick RGH). Consequently, research and development people turned their attention to the reduction of eddy current loss. It was known at the time that eddy current loss can be reduced by decreasing the sheet thickness, raising the Si content to increase electric resistance, or reducing the 180° domain wall spacing by reducing the grain diameter.[9)] Even a current technical levels, however, it is no easy matter to reduce the sheet thickness and grain diameter without also causing deterioration of the textural orientation because of the reciprocal metallurgical relationship existing between these factors. Section 4 details Kawasaki Steel's development of thin gauge grain-oriented silicon steel sheets 0.23 mm in thickness (23RGH), in which several new metallurgical techniques were used.[10,11)] Following the introduction of 23RGH, even thinner sheets of 0.20 mm and 0.18 mm have been developed,[12)] and have won strong acceptance from transformer makers, especially in the U.S.

In contrast to the metallurgical method described above, new methods based in physical science have also been developed for reducing eddy curent loss, includig the physical reduction of the 180° domain wall spacing. One such technique involves the application of a surface coating with a low coefficient of thermal expansion; the tension introduced by this coating can reduce iron loss on the order of several percent.[13,14)] In another method, refinement of the magnetic domain is achieved by introducing local strain in the sheet following secondary recrystallization. The originally proposed method of scribing or inducing strain with steel balls, however, was not commercially feasible.[15-17)] Industrial-scale production of strain-induced silicon steel was realized by Nippon Steel Corporation, using pulse-laser irradiation (product name, ZDKH),[18)] and then by Kawasaki Steel, using a plasma-jet irradiation method (product name, RGH · PJ),[19)] giving Japan world leadership also in this area of technology. More recent development efforts have focused on domain-refining techniques compatible with stress relief annealing.[20)] **Figure 1** summarizes the foregoing discussion of progress in the reduction of iron loss in silicon steel sheets over the last four decades.

3 Methods of Reducing Eddy Current Loss

Magnetization of grain-oriented silicon steel sheets is generally accomplished by domain wall displacement of the 180° domain, which is the main domain. Changes in the flux which accompany domain wall displacement, however, cause eddy currents and result in eddy current loss.

The classic definition of eddy current loss (P_{cl}) is given by the following formula, which applies when changes in magnetization are uniform:

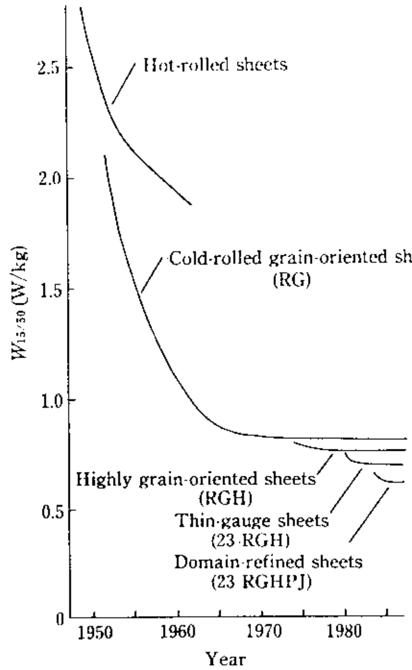


Fig. 1 Historical iron loss improvement of silicon steel sheets

$$P_{cl} = (\pi d B_m f)^2 / 6\rho \qquad (\mathrm{W/m^3})$$

where d: thickness of sheet
B_m: maximum flux density
f: frequency
ρ: specific resistance

Pry and Bean[21] concluded that eddy curent loss P is given by the following formula when the 180° domain wall moves sinusoidally relative to time and the domain wall spacing is greater than the sheet thickness.

$$P = 1.63\, P_{cl}(2L/d) \qquad (\mathrm{W/m^3})$$

In this formula, L represents 180° domain wall spacing. As can be seen, eddy current loss decreases as the sheet becomes thinner, as the specific resistance increases, or as the 180° domain wall spacing becomes narrower.

The 180° domain wall spacing is determined in such a way as to minimize the sum of the magneto-static energy due to magnetic free poles at the grain boundaries and the sheet surface, domain wall energy, and magneto-elastic energy caused by strain. More concretely, the 180° domain wall spacing is determined by crystalized grain size, the tilt angle of the Goss texture, tensile stress introduced by surface coating, and other factors. When tilt angle and stress are fixed, domain wall spacing is known to be proportional to $\sqrt{D}$ (D: Crystalized grain diameter).[22] For practical applications this means that by reducing the grain size, the domain wall spacing can also be decreased, thereby reducing the magneto-static energy caused by the magnetic free poles which occur at the grain boundaries. To summarize these points, eddy current loss can be reduced by reducing the thickness of the sheet, increasing its Si content in order to raise specific resistance, or reducing grain size.

4 Development of Thin Gauge Grain-Oriented Silicon Steel Sheet RGH

The principal material-related factors which control eddy current loss, as discussed above, have been investigated by Littmann[9] and a number of other researchers. On the other hand, while these factors—sheet thickness, Si content, and grain size—greatly affect iron loss, their relationship to iron loss is not a simple one. In addition, the reduction of iron loss has a minimum limit. The explanation of these facts is that changes aimed at reducing eddy current loss tend to increase hysteresis loss, which is one of the two main components of iron loss.

Increased hysteresis loss results from an increasingly large misalignment of the secondary-recrystallized grain orientation relative to (110)[001], i.e. Goss orientation, and a failure to obtain an adequate secondary-recrystallization structure, both of which are factors causing deterioration of grain orientation.

Although research indicated that the minimum limit on iron loss was in the sheet thickness range of 0.15 to 0.20 mm, at the beginning of the 1980s only sheet as thin as 0.27 mm had been commercially produced. Even assuming thinner steel sheet products were manufactured, consistently good high grain orientation could not be guaranteed, making it impossible to produce to low iron loss products. A true low iron loss product, as described below, was realized in the thin gauge grain-oriented silicon steel sheet RGH by a combination of techniques aimed at reducing eddy current loss. These included not only techniques for reducing in thickness, increasing the Si content, and reducing grain size without adversely affecting texture orientation.

4.1 Increased Si Content

Figure 2 shows the relationship between the Si content of commercially produced RGH and iron loss. Although the Si content of conventional RGH was 2.9%, advances in cold-rolling technology have made it possible to roll steels with higher Si contents, allowing a reduction in iron loss of 0.1 W/kg in comparison with the conventional product.[23] It was generally known that an increased Si content improves iron loss performance by increasing the specific resistance of the material, but other factors made it difficult to obtain the originally hoped-for effects. Specifically, the coarse elongated grains which are created by hot rolling suppress the formation of secondary-recrystallized grains in the high-temperature final annealing process. To solve this problem, the C content of the material was increased in

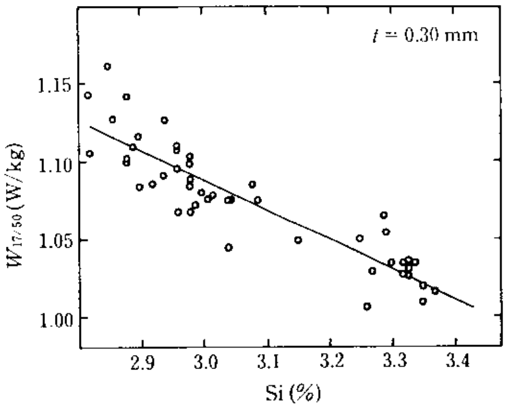


Fig. 2 Effect of Si content on iron loss

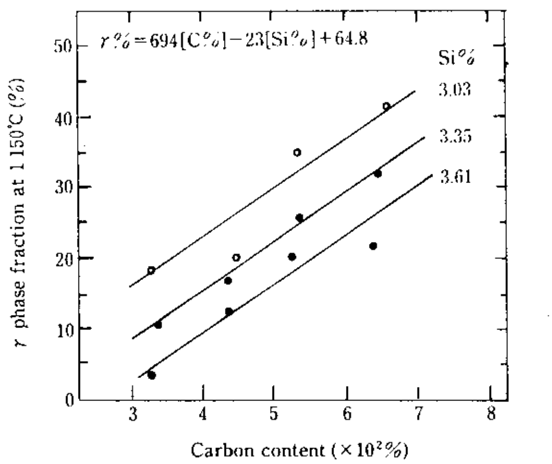


Fig. 3 γ phase fractions at 1 150°C as a function of carbon and silicon contents

proportion to the increase in Si content. This measure improves the texture of hot-rolled sheets by promoting formation of an austenite phase, which is necessary during hot rolling.[24] **Figure 3** shows laboratory results for the γ-phase content at 1150°C obtained with materials of varying C and Si contents. Based on the relationship shown in this figure, appropriate levels of C addition can be determined for various Si contents.

4.2 Reduced Grain Size

The size of the grain of the finished product depends on the number of secondary-recrystallized grains generated during final high temperature annealing. In turn, the frequency of generation of secondary-recrystallized grains depends on the primary-recrystallized texture formed during decarburization annealing prior to high-temperature final annealing and the strength of the inhibitors (in RGH, fine precipitates of MnSe and grain-boundary segregated Sb) used to restrain the normal grain growth of the grains. In RGH, which is subjected to a two-stage cold-rolling process, the size of second-

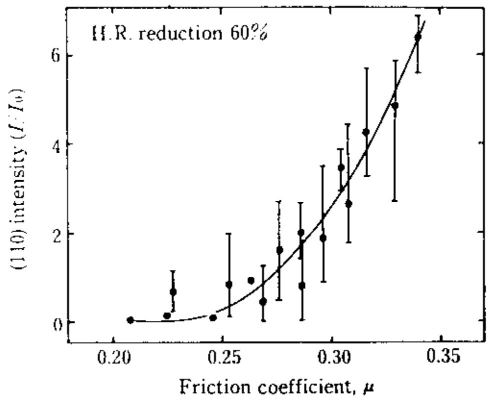


Fig. 4 Change of (110) intensity in the surface texture of hot-rolled sheet by frictional force during hot rolling

ary-recrystallized grains is inversely proportionate to the intensity of the Goss orientation component in the primary-recrystallized texture. Tracing the origin of the Goss orientation upstream to the hot-rolling process, the intensity of the Goss orientation component of the primary-recrystallized texture is positively related to the intensity of the Goss orientation of the surface layer of the hot-rolled sheet.[25]

An effective means of increasing the Goss intensity in hot rolling is to increase the coefficient of friction between the sheet and rolls, as can be seen from **Fig. 4**. The coefficient of friction is affected by rolling speed and temperature and roll surface lubrication. Proper control of these various factors, within the range in which inhibitor function will not be affected, makes it possible to obtain a strong Goss orientation component in the hot-rolled texture, which is advantageous from the viewpoint of refinement of secondary-recrystallized grains.

A second method on increasing the Goss intensity requires that very fine carbides on the order of 10 nm be made to precipitate minutely and disperse in the sheet prior to final cold rolling. It was formerly believed that solute carbon was more effective than carbides in the formation of the Goss orientation component.[26] As shown in **Fig. 5**, however, if the finest possible carbides are precipitated using a pattern of quenching in the high temperature region followed by slow cooling at low temperature as the intermediate annealing process preceding final cold rolling, the intensity of the Goss orientation component in decarburized sheet will intensify to a greater degree than if C is allowed to remain in solution.[27]

Using these two methods it is possible to reduce the size of the secondary-recrystallized grains in the final product without causing the deterioration of textural properties. As shown in **Fig. 6**, each 1-mm reduction in grain diameter results in a reduction of approximately

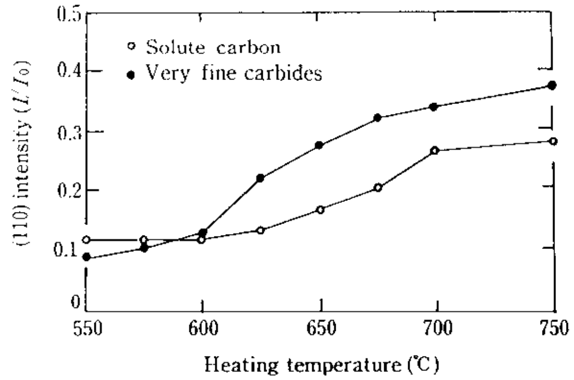


Fig. 5 Effect of carbon morphology on (110) pole intensity of recrystallized texture

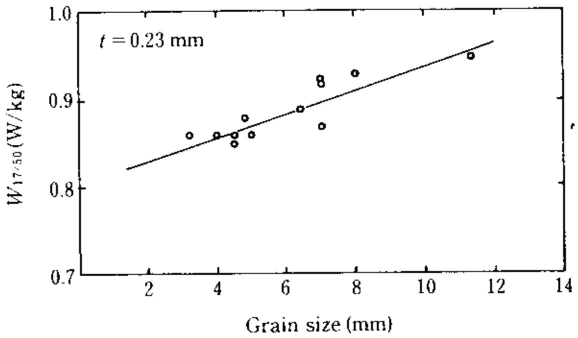


Fig. 6 Effect of grain size on iron loss

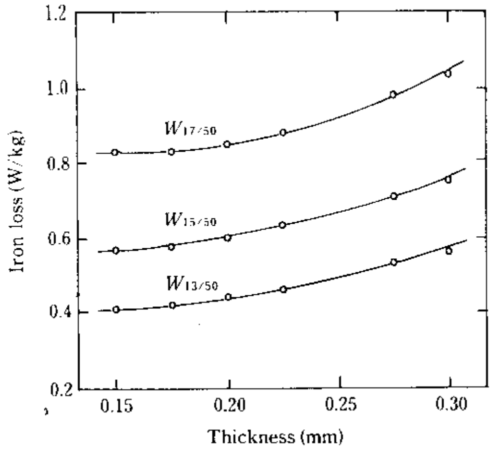


Fig. 7 Effect of thickness on iron loss

0.01 W/kg in iron loss.

4.3 Reduction of Sheet Thickness

In the heating process for high-temperature final annealing, RGH is given long-time soaking at a temperature between 800°C and 950°C. It is a feature of this product that this process is used to promote formation of the Goss orientation.[6] During the soaking period, the inhibitors decompose and dispersion toward the surface layer has been observed. This phenomenon becomes more pronounced with thinner sheets, since the surface area/volume ratio of the material increase, and results in unsatisfactory inhibitor performance. As a consequence, the desired secondary-recrystallization structure is not obtained and texture orientation deteriorates. When manufacturing thin-gauge products it is therefore necessary to use stronger inhibitors. At the same time, it is essential that the cold-rolling reduction ratio and annealing conditions be adjusted to obtain an appropriate primary-recrystallization texture.

The relationship between thickness and iron loss in commercial products is shown in **Fig. 7**. In comparison with the 0.30-mm thickness, formerly the most commonly used specification, a reduction in iron loss of approximately 15% has been obtained with material 0.23 mm thick. The reduction is approximately 20% with a 0.15-mm product.

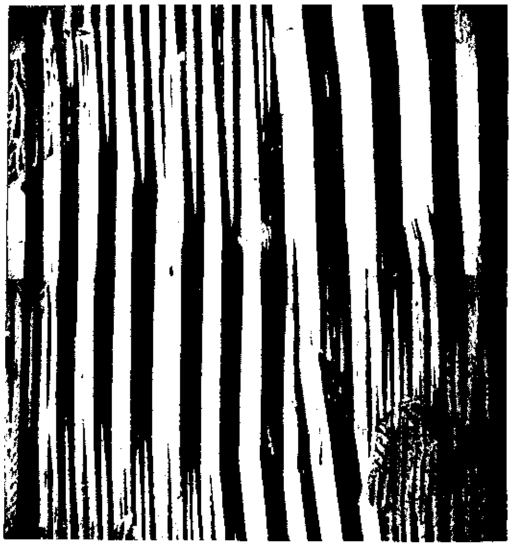
5 Domain Refining Technique Using Plasma Jet Irradiation

As discussed in the previous section, thin-gauge grain-oriented silicon steel sheets are produced using metallurgical techniques for the reduction of eddy current loss. On the other hand, the domain refining technique is used as a physical method of reducing eddy current loss.

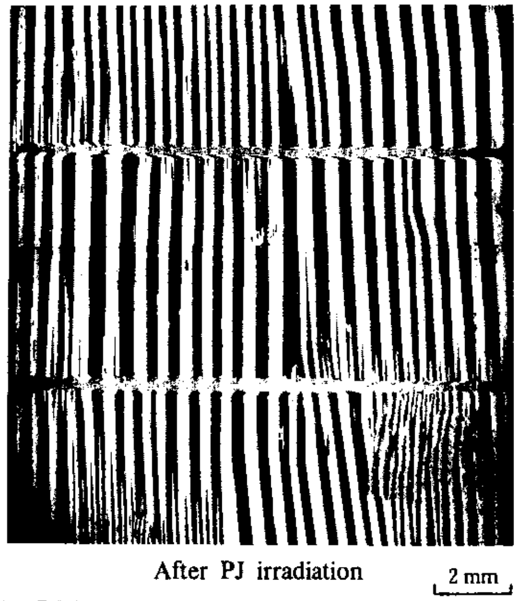
Eddy current loss decreases as the grain size becomes smaller and the domain wall spacing is reduced, as was discussed in Sec. 3. The principle of domain refining involves the introduction of local strain in the steel sheet after secondary recrystallization, and the use of this local strain, as though it were in fact a grain boundary, to reduce the domain wall spacing. The application of the domain wall refining technique makes it possible to achieve simultaneously two generally mutually incompatible aims: the reduction of hysteresis loss by developing a highly oriented Goss texture and the reduction of eddy current loss by reducing grain size. As a result, it is possible to further reduce iron loss in thin-gauge grain-oriented silicon steel sheets. A domain refining technique using plasma jet irradiation, and the application of this technique to RGH will be discussed in the following.

5.1 Plasma Jet Irradiation

Heating gas to high temperature gives rise to violent collisions among the gas particles, causing the separation of electrons and positively charged ions. This electrically neutral compound of electrons and positively charged ions is called plasma. The high temperature energy available in plasma has found a wide range of applica-



Before irradiation



After PJ irradiation

Photo 1 Domain refining by PJ irradiation

tions, from spray deposition to nuclear fusion.

A plasma jet (PJ) is used in the refinement of domain wall spacing. In this technique, the gas is transformed into plasma by an arc discharge. The plasma is forcibly cooled and restricted by a nozzle orifice and high speed gas flow, and as a result of this "thermal pinch" effect the plasma leaves the nozzle as a jet of even higher temperature than the originally generated plasma. The temperature of central zone of a plasma is in excess of 10 000°C.

When this type of high-temperature, high-energy plasma jet is irradiated for short periods onto the surface of a steel sheet perpendicular to the rolling direction, domain refining can be effected with absolutely no damage to the surface coatings of the sheet. As a result of strains introduced by the plasma jet, domains in the sections of the sheet subjected to plasma jet irradiation are transformed into what are called "stress pattern domains," in which the magnetization of the sheet interior lies in the [100], [010] directions. As shown in **Photo 1**, by introducing the stress patterns as though they were grain boundaries to reduce the magneto-static energy caused by the magnetic free poles generated at the interface between the stress pattern and the 180° domain, a reduction in the 180° domain wall spacing can be achieved.

Plasma jet irradiation is conducted at intervals in the rolling direction. For the most effective domain refining, the irradiation interval should be inversely related to the grain size of the material. Plasma jet irradiation introduces additional grain boundaries and reduces effective grain diameter to a degree which depends on the irradiation interval and original grain diameter (D). The optimum irradiation interval l_{opt} at which the effective grain diameter corresponds to the optimum grain diameter (K_o) and iron loss has been known to have a minimum value is given by:

$$l_{opt} = K_oD/(D - K_o)$$

As can be understood from the formula, the greater D is, the smaller the value of l_{opt} must be.

5.2 Magnetic Characteristics of Plasma Jet-Treated Materials

Figure 8 shows iron loss $W_{17/50}$ before and after plasma jet irradiation of the material (0.23 mm in

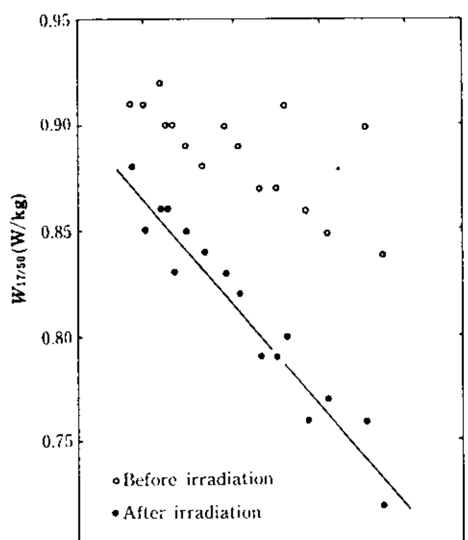


Fig. 8 Iron loss before and after plasma-jet (PJ) irradiation

thickness). It has been verified that iron loss reductions obtained by plasma jet irradiation are positively related to B_8 value and that a maximum iron loss reduction of about 16% can be achieved. Further, the relationship between iron loss after plasma jet irradiation and the B_8 value is a linear function, with reductions in iron loss being proportional to the B_8 value. This can be explained by the fact that, regardless of grain size, eddy current loss upon irradiation decreases to the same level. Iron loss in plasma jet-irradiated sheets therefore depends on hysteresis loss, and hysteresis loss decreases linearly in proportion to the B_8 value. The greatest advantage of this type of domain refining technology is that iron loss can be reduced even when the grain size is large, provided the orientation of the secondary-recrystallized texture can be enhanced. This has made it possible to achieve new levels of iron loss reduction.

Figure 9 shows the compressive stress sensitivity of magnetostriction in the rolling direction before and after plasma jet irradiation. Compressive stress sensitivity is improved by plasma jet irradiation, indicating that some significant degree of tensile stress is added by irradiation. This additional tensile stress also contributes to the refinement of the magnetic domains.

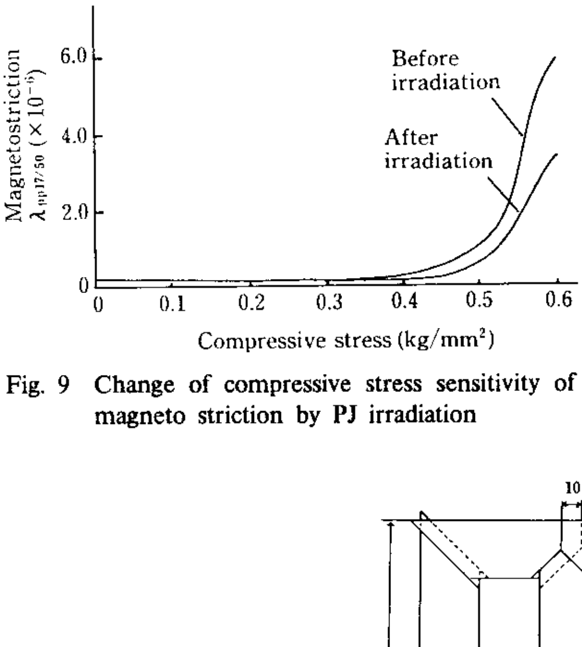


Fig. 9 Change of compressive stress sensitivity of magneto striction by PJ irradiation

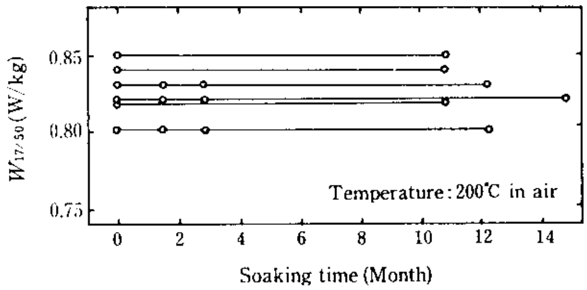


Fig. 10 Soaking-time dependency of iron loss of PJ-irradiated sheets

To confirm the stability of the magnetic properties of plasma jet-irradiated sheets at normal operating temperatures for transformer cores, which run as high as approximately 130°C, an investigation of aging deterioration was conducted. The results are shown in **Fig. 10**. In this aging test, under conditions of 200°C for a maximum of 15 months, no deterioration of iron loss properties was found with the plasma jet-irradiated sheets, indicating that no significant relaxation of the stresses induced by plasma jet irradiation occurs at the temperatures under which transformer cores normal operate.

5.3 Magnetic Properties of Transformers with Plasma Jet-Irradiated Materials

In order to examine the magnetic properties of transformers constructed of plasma jet-irradiated materials, two models transformers were assembled, as shown in **Fig. 11**. The materials used were 0.23-mm-thick RGH · PJ, which had been subjected to plasma jet irradiation, and standard RGH, to which the plasma jet

Fig. 11 Joint configurations of model transformer

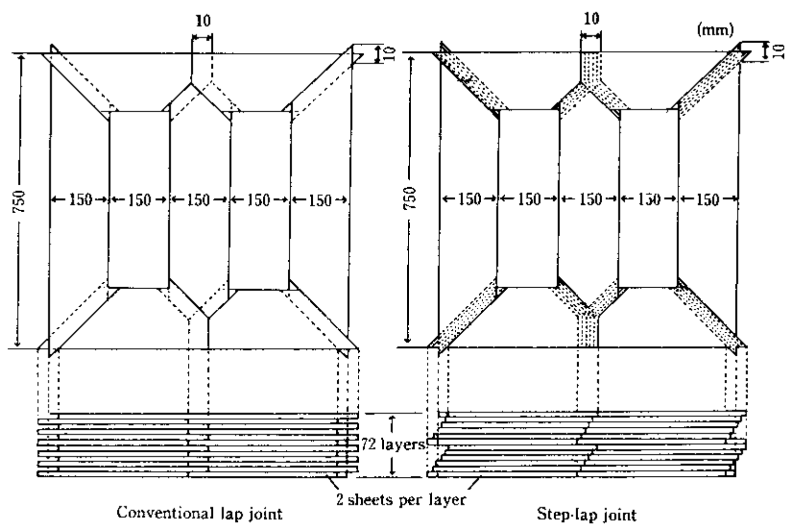


Table 1 Iron loss of model transformers

Sheets grade	Magnetic properties of sheets		Magnetic properties of model transformer cores			
			Conventional lap joint		Step-lap joint	
	B_8 (T)	$W_{17/50}$ (W/kg)	$W_{17/50}$ (W/kg)	B.F.	$W_{17/50}$ (W/kg)	B.F.
RGH	1.89	0.91	1.08	1.19	1.06	1.16
	1.89	0.92	1.09	1.18	1.07	1.16
RGH-PJ	1.90	0.84	1.00	1.19	0.97	1.15
	1.90	0.84	1.01	1.20	0.98	1.17

treatment is not given. The magnetic properties of the materials as well as of the model transformers are shown in **Table 1**. With both the conventional lap joint and the step-lap joint, RGH · PJ was superior to RGH in iron loss, while the building factor (B.F., the ratio of transformer core iron loss/original material iron loss) of RGH · PJ was virtually the same as that of RGH. Thus it can be predicted that the properties of the original material will be retained and reflected in actual equipment.

Because permeability and eddy current loss are reduced in domain-refined materials, a lower building factor was expected with the RGH · PJ.[28,29] The building factor of the RGH · PJ, however, was virtually identical to that of the non-domain refined material. The presumed reason for this is as follows: In domain-refined material, the magnetic flux in the strain-induced area may be transferred to the upper and lower sheets, but because this transferred flux includes a sheet normal component, the transfer causes eddy current loss and thus contributes to iron loss. It is therefore considered that the transfer of magnetic flux offsets the reduction in building factor expected in domain-refined sheets.

Both Japanese and foreign makers of stacked-type transformers have already adopted RGH · PJ, and have obtained the same excellent magnetic properties in actual transformers as were found with the model units described above.

6 Conclusions

In response to the need for better iron loss performance in transformer cores, thin-gauge grain-oriented silicon steel sheet RGH and domain-refined RGH · PJ were developed. With RGH, techniques for obtaining thinner sheets with higher Si contents and reduced grain size without causing deterioration of the Goss texture orientation were introduced. With RGH · PJ, a plasma jet is used to introduce local strain in the steel sheet without causing damage of the sheet coatings. Domain refining is accomplished by using the strain-induced areas as though they were grain boundaries, and results in reduced iron loss.

This type of steel sheet offers significant improvement in iron loss over that of conventional products, and by enhancing transformer efficiency is expected to make a major contribution to energy conservation.

References

1) Office of the Minister of International Trade and Industry: *Kikai-Tokei-Geppo (Monthly Report on Machinery Statistics)*, Aug (1988)
2) Henden-Kiki-Sho-Energy Senmon-Iinkai (Special Conference on Transformer Energy Savings): Denki Kyodo-Kenkyu (*Cooperative Research on Electricity*), **40**(1984), 4
3) M. Sato, H. Fukagawa, and M. Kato: Denryoku-Chuo-Kenkyu-Hokoku (Report of Central Research Institute on Electric Power), Research Report 685016, (1987)
4) Y. Nishiyama and M. Nakajima: *Tetsu-to-Hagané*, **20**(1934)1, 1
5) S. Taguchi: Nihon Kikai Gakkai-Shi (J. Jpn. Soc. Mechanical Engineers), **81**(1978)710, 46
6) Kawasaki Steel Corp.: Jpn. Kokoku 36-17154
7) S. Taguchi and A. Sakakura: *J. Appl. Phys.*, **40**(1969)3, 1539
8) I. Matoba, T. Imanaka, K. Matsumura, T. Goto, T. Ichida, T. Kan, S. Kobayashi, B. Fukuda, and J. Hirata: *Kawasaki Steel Giho*, 7(1975)2, 175
9) M. F. Littman: *J. Appl. Phys.*, **38**(1967)3, 1104
10) S. Yamada, Y. Obata, and T. Sadayori: *Tetsu-to-Hagané*, **66**(1980)11, S1159
11) H. Shimizu, H. Shishido, Y. Ito, and Y. Shimanaka: Magnetics Kenkyukai Shiryo (Magnetics Research Paper), MAG 81-35, (1981), [Inst. Electrical Engineers of Japan]
12) Y. Iida, K. Iwamoto, M. Sakaguchi, and Y. Ito: Proc. of ASM Conf. of Hard and Soft Magnetic Materials, 8710-007, (USA), (1987)
13) Nippon Steel Corp.: U.S. Patent No. 385668
14) H. Shimanaka, T. Ichida, S. Kobayashi, and T. Funahashi: *IEEE, Trans. Mag.*, MAG-15, No. 6 (1979), 1595
15) Mannesmann: Jpn. Kokoku 50-35679
16) T. Yamamoto and S. Taguchi: Proc. SMM-2, (Czechoslovakia), (1975), 15
17) Nippon Steel Corp.: Jpn. Kokoku 58-5963
18) Nippon Steel Corp.: Jpn. Kokoku 57-2252
19) B. Fukuda, K. Sato, T. Sugiyama, A. Honda, and Y. Ito: Proc. of ASM Conf. of Hard and Soft Magnetic Materials, 8710-008, (USA), (1987)
20) H. Kobayashi, K. Kuroki, E. Sasaki, M. Iwasaki, and N. Takahashi: Physica Scripta, T24, (1988), 36
21) R. H. Pry and Bean: *J. Appl. Phys.*, **29**(1958), 532
22) B. Fukuda, K. Sato, T. Ichida, Y. Ito, and H. Shimanaka: *IEEE Trans. Mag.*, MAG-17, No. 6 (1981), 2878
23) H. Shimanaka, Y. Shimizu, T. Goto, Y. Iida, and U. Nishiike: Proc. of TMS-AIME Symposium, (USA), (1980), 157
24) R. L. Rikett and N. C. Fick: *Trans. AIME*, 167(1946), 346
25) Y. Shimizu, Y. Ito, and Y. Iida: *Metallurgical Transactions*, 17A (1986), 1323
26) H. Abe, and K. Takagi: *Tetsu-to-Hagané*, **57**(1971)7, 1123
27) Y. Iida, K. Iwamoto, K. Goto, I. Matoba: *Proc. of ICOTOM*, 7(1984)607
28) B. Fukuda, K. Sato, Y. Shimizu, and Y. Ito: *J. Appl. Phys.*, 55(1984)6, 2130
29) A. Sakaida, and A. J. Moses: EPS Conf. on SMM, (1985)