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History and Recent Development of Grain Oriented Electrical Steel at Kawasaki Steel*


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1 Introduction

In grain oriented electrical steel, the grains comprising the sheet assume the (110)[001] orientation, which is called the Goss orientation. This steel is produced from 3% Si-steel, which possesses extremely good magnetic properties in the rolling direction, and is indispensable as the core material for transformers. A transformer has two types of electrical power losses, iron loss, which originates in the core material used, and copper loss, which originates in coil resistance. According to power statistics for fiscal 1995, the total loss attributable to transformers during power transmission in Japan is approximately 17 billion kWh annually, which correspond to 1.7% of total generated power. Iron loss was estimated at 10 billion kWh, or approximately 60% of total loss. Moreover, demand for electric power will of course tend to increase in the future in Japan, and in the developing nations as well, heightening the need for energy efficiency as part of the solution to the global environmental problem. Thus, the use of core materials with small loss is a matter of extremely large significance, even when considered on the global scale.

Kawasaki Steel began research and development on grain oriented electrical steel shortly after the Second World War, and first succeeded in producing a grain oriented electrical steel with wide-width strip product using independently developed technology in the 1960s. From that time until the present, the company has endeavored to develop and provide a stable supply of high grade products, aiming consistently at lower iron loss. Although the basic method of manufacturing grain oriented electrical steel was developed in the United States in the mid-1930s, the revolutionary improvement in quality and establishment of mass production technology in the last quarter century were achieved in Japan, with the result that Kawasaki Steel, together with Nippon Steel Corp., now plays the world's leading role in this field.

The following paper presents an outline of the history of technical development at Kawasaki Steel, and discusses recent progress and the outlook for the future.

2 History of Development of Grain Oriented Electrical Steel

The development of grain oriented electrical steel at Kawasaki Steel began in 1948, when the company was still a division of Kawasaki Heavy Industries, Ltd. Initially, this work began with small-scale experiments in an unpretentious laboratory at Fukiai Works and centered on the temper rolling method, aiming at low-cost commercialization. Full-scale development began when a G15 equivalent product was obtained by the Goss

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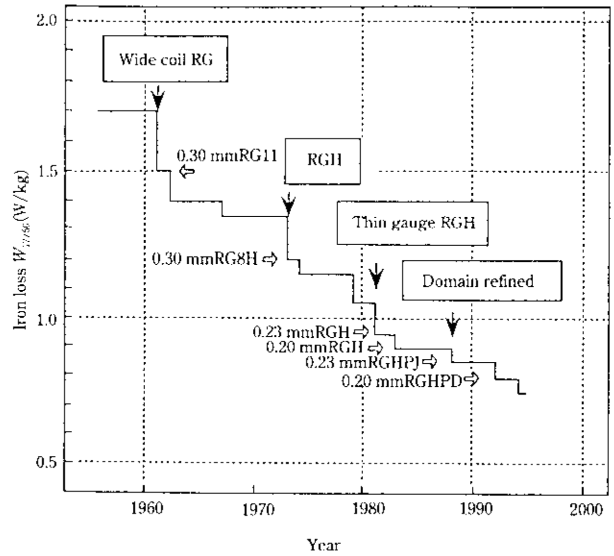

Fig. 1 Historical trend of iron loss improvement in Kawasaki Steel

process[1] in early 1955. This chapter will briefly review the history of grain oriented electrical steel at Kawasaki Steel from 1955 until recent years.

One of the features of the grain oriented electrical steel produced by Kawasaki Steel is the use of MnSe as an inhibitor element, which is indispensable for the control of grain orientation, and is the result of repeated experiments with actual coils beginning in 1959. At that time, the mainstream method worldwide was a 2-stage cold-rolling process using an MnS inhibitor, as taught by the American company Armco Steel Corp.[2,3] However, a group of Kawasaki Steel engineers who were seeking a path to independent development investigated a large number of grain boundary segregating elements. During this research, the group discovered that MnSe is superior to MnS in its inhibiting effect for grain boundary movement,[4] and then succeeded in realizing an industrial process.[5] Initially, the scale of production was small, using a narrow-width line. However, with the introduction of No. 1 Sendzimir mill at Fukiai Works and the startup of a continuous annealing line, it became possible in 1961 to supply a wide-width product in thicknesses of 0.35 mm and 0.30 mm under the trade name RG (RG11: iron loss specification $W_{15/50} < 1.15$ W/kg (0.35 mm), 1.10 W/kg (0.30 mm)), and production increased rapidly.

The history of progress in electrical steel is often said to be the history of improvement in iron loss. Likewise, Kawasaki Steel also developed several major technologies which improved iron loss after this initial success. **Figure 1** shows the history of iron loss improvement at Kawasaki Steel. The level of iron loss in recent years has reached approximately 1/2 that in 1960. The following will describe the major improvement techniques during this period.

2.1 Development of RGH

The magnetic properties of grain oriented electrical steel are evaluated in terms of both induction and iron loss. If a core material with good induction is used, it is possible to reduce the exciting current and make the equipment more compact. On the other hand, if electrical equipment with a core material having good iron loss is used, the amount of energy which is lost as heat is reduced, and savings in power consumption are possible. Based on the tendency in the United States and Europe to give priority to iron loss, Kawasaki Steel considered improvement in flux density (permeability) as a means of improving iron loss, and consistently conducted research and development aimed at lowering iron loss. However, in 1968, Orient core "Hi-B" was announced by Yawata Works of Nippon Steel Corp.[6] and received a high evaluation from customers, giving impetus to the development of a high permeability material at Kawasaki Steel as well. This development required approximately three years, but in 1973, Kawasaki Steel began sales of its own high permeability grain oriented electrical steel under the trade name "RGH."[7]

Because a strong inhibitor, which will cause selective growth of Goss nuclei of near-ideal orientation, is indispensable for improving the alignment of grain orientation, the development of a new inhibitor was the most important task. Among inhibitors, the existence of two types was known. One type forms fine precipitates such as sulfides and nitrides whose pinning effect inhibits normal grain growth of primary recrystallized grains, whereas the other type inhibits grain growth by the drag effect of solute atoms with a tendency of boundary segregation. The first essential point in the development of RGH was the discovery that a stronger inhibiting effect is obtained by the complex effect of these two types of inhibitors. Specifically, as shown in **Fig. 2**, it was possible to significantly enhance the grain growth inhibiting effect of the MnSe inhibitor used with RG by a complex addition of Sb.[8,9] It is known that secondary recrystallization of Goss grains becomes difficult when second rolling reduction is greater than 60% because the (110) intensity of the surface layer of the primary recrystallization texture, namely, the Goss intensity, is generally reduced. On the other hand, alignment to the Goss orientation is enhanced as cold rolling reduction increases. Increasing the inhibiting force of the inhibitor made it possible to adopt a second rolling reduction of 60–70%, which is 10% or more higher than that in the preceding Goss process, and this in turn made it possible to produce grain oriented electrical steel with an orientation closer to the ideal.

One other essential point in the development of RGH was the introduction of two step soaking process in final box annealing in order to complete secondary recrystallization at the lowest possible temperature. The results of a detailed investigation of the secondary recrystalliza-

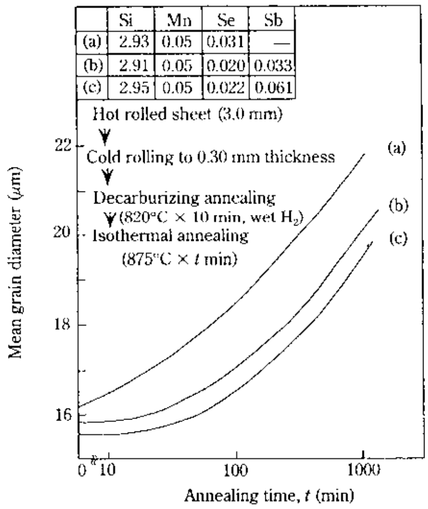

Fig. 2 Effect of mixed inhibitors, Se and Sb on the normal grain growth of primary recrystallization grains

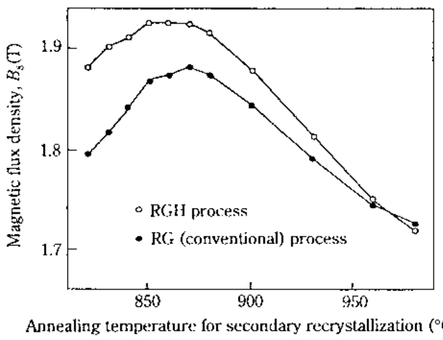

Fig. 3 Effect of secondary recrystallization temperature on magnetic flux density B_8 of RG and RGH

tion conditions for selecting grains closer to the ideal orientation out of the numerous Goss nuclei yielded the important knowledge that Goss grains of near-ideal orientation tend to be secondary grains whose nuclei were formed at lower temperatures, and application of this finding to actual coils was studied as an effective method. Generally, the heating rate in final annealing performed on an industrial scale is decided by the size of the coil and the heat capacity of the furnace. The actual rate was normally 20–30°C/h, and secondary recrystallization began at 900°C or higher. As a measure for lowering the secondary recrystallization temperature by 50°C or more, a two-step annealing process, which includes low-temperature, long-term holding for secondary recrystallization, was adopted. As shown in **Fig. 3**, this made it possible to obtain B_8 values of 1.88T or higher stably.

Two points which should also be emphasized here are the application of a satisfactory film formation technique,[10] which was developed at about the same time as

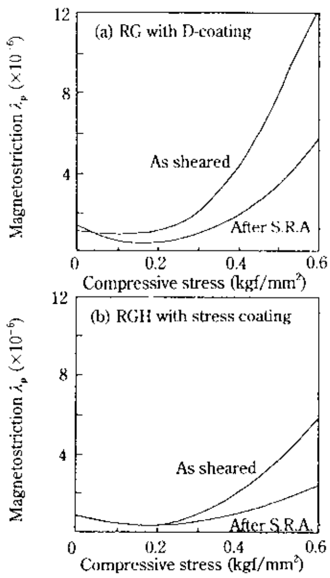

Fig. 4 Stress sensitivity of magnetostriction of RGH with the stress coating and of RG with conventional phosphate coating

Table 1 Basic manufacturing process of RG and RGH

Process	RG	RGH
Steel making (inhibitor elemnets)	MnSe or MnS	MnSe and Sb
Hot rolling (finished thickness)	2 mm	3 mm
1st cold rolling	70%	75%
Intermediate ann.		
2nd cold rolling	50%	65%
Decarburization ann.		
Box annealing	1 step heating with relatively high heating rate	2 step heating with secondary recrystallization stage at 820–900°C
Coating and flattening	Phosphate coating	New phosphate coating

the basic RGH process was established, and a new insulating coating.[11,12] The new coating had a markedly lower thermal expansion coefficient than the conventional coating, and could therefore be used to apply strong tensile stress to the steel sheet. Iron loss was reduced by applying the coating to highly oriented RGH, and, as shown in **Fig. 4**, the coating was also remarkably effective in reducing magnetostriction, contributing to lower noise in transformers.

Although the feature of RGH production process was increased cold rolling reduction by enhancing the inhibitor used with the conventional material, it was still in the scope of the Goss process, 2-stage cold-rolling process with intermediate annealing, as shown in **Table 1**. This method has two advantages: first, due to the large number of Goss nuclei, secondary recrystallization is easier and fluctuations of magnetic properties are small,

Table 2 Typical magnetic properties of RG and RGH in 1974

Thickness	0.30 mm		0.35 mm	
Grade (JIS)	$W_{17/50}$ (W/kg)	B_8 (T)	$W_{17/50}$ (W/kg)	B_8 (T)
RG10	1.23	1.85	1.35	1.85
RG9	1.17	1.86		
RG9H			1.30	1.88
RG8H	1.17	1.88	1.24	1.89
RG7H	1.11	1.89		

and second, owing to the relatively small grain size in finished products, low iron loss is easily obtained. **Table 2** shows the typical magnetic properties of RGH at the time of development. In the beginning stage, commercially supplied RGH was only thicker gauge of 0.30 mm and 0.35 mm. After that a technology for high purification and improvement of the orientation alignment was developed, and by increasing the Si content and other means,[13] the product was upgraded in 1979 to RG6H (thickness: 0.30 mm, $W_{17/50}$: ≦ 1.05 W/kg). The production technology for RGH was exported to Surahammars Brucks AB in Sweden, and has gained an excellent worldwide reputation.

2.2 Development of Thin Gauge Grain Oriented Electrical Steel RGH

Following the successive Oil Crises which occurred in 1974 (1st) and 1979 (2nd), demand for transformer core materials with lower iron loss increased by the year as part of a rising world trend toward energy saving resulting from the rapid rise in energy prices. Kawasaki Steel promptly began development of thinner-gauge grain oriented electrical steel as a new means of improving iron loss. The thinnest product thickness at the time was 0.27 mm. Although eddy current loss is reduced by decreasing the product thickness, conversely, hysteresis loss increases as the sheet thickness is reduced. As shown in **Fig. 5**, the sheet thickness for minimizing total loss, which is the sum of the eddy current and hysteresis loss, is between 0.15–0.23 mm.[14] This fact was widely known; however, secondary recrystallization behavior became unstable as the product thickness became thinner, and the fact that it was difficult to obtain the calculated iron loss improvement effect was a problem. Moreover, since thinner gauge products increased the labour cost for stacking in transformer makers, electrical steels with thinner gauges were not yet welcomed at that time.

The initial development targets were commercial RGH products with gauges of 0.20 mm and 0.23 having the iron loss, $W_{17/50}$ of 0.90 W/kg or under. The development proceeded with the conformation of basic RGH process to thinner gauge, focusing on cold rolling and annealing conditions to stabilize secondary recrystallization. The optimum balance of reduction between first and second cold rolling did not change greatly even with

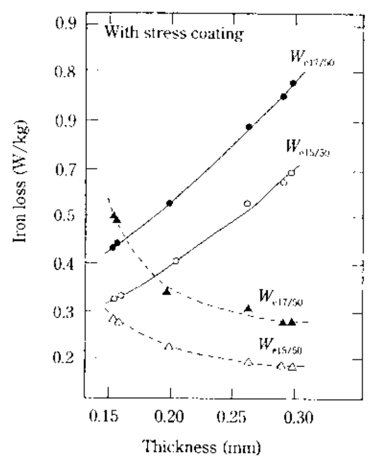

Fig. 5 Influence of thickness change on eddy current loss and hysteresis loss

thinner gauge products, and it was possible to meet this requirement by reducing the thickness of the hot rolled strip. However, obtaining secondary recrystallization with good orientation alignment in a stable manner was not so simple.

The first problem was that the grain size of the secondary recrystallized grains increased, and as a result, the target iron loss was not achieved. As one countermeasure, methods of increasing the density of Goss nuclei in the primary recrystallization texture were studied. The first method was to enhance the Goss intensity in the surface layer of the hot rolled strip by controlling the hot rolling process which is the origin of Goss orientation. Because high-friction hot rolling is effective in enhancing the Goss intensity, a rolling speed and a rolling pass schedule which would increase the friction coefficient between the rolls and strip was selected.[15] As a second method, it was possible to increase the density of Goss nuclei by reducing the mobility of dislocation during cold rolling and thus promoting the formation of a cell structure, which is achieved by dispersing the fine carbides in the steel strip before second cold rolling.[16] For this, a special heat pattern was adopted in intermediate annealing, combining a rapid quench after the completion of soaking, followed by slow cooling at low temperature. Thus, the technology for secondary grain refinement was established, making it possible to produce thin gauge grain oriented electrical steel which satisfied the target iron loss, as shown in **Fig. 6**. In addition to the above, it was necessary to solve numerous other problems before commercial production became possible, including the development of a thin film formation technique to avoid reduction in the spacing factor[17] and operating techniques that did not deteriorate appearance and shape.

In 1981, development of the commercial product was finally completed, and publicity activities began in the summer.[18] **Table 3** shows the specification of iron loss

Table 3 Specification and typical magnetic properties of thin gauge RGH in 1983

Grade	Thickness	Specification		Typical magnetic properties		
		$W_{15/60}$(W/1b)	$W_{17/50}$(W/kg)	$W_{15/60}$(W/1b)	$W_{17/50}$(W/kg)	B_8(T)
8 mil MOH	0.20 mm	≦0.38	≦0.98	0.36	0.88	1.89
9 mil MOH	0.23 mm	≦0.40	≦1.00	0.38	0.92	1.89

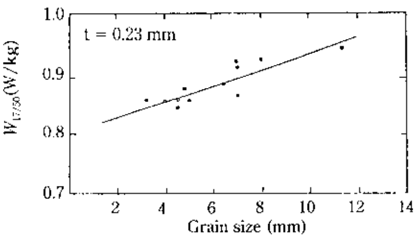

Fig. 6 Relationship between grain size of grain oriented electrical steel and iron loss

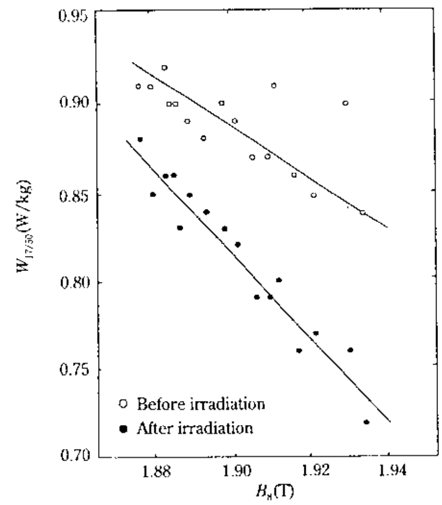

Fig. 7 Iron loss before and after plasma jet irradiation

and typical magnetic properties of the thin gauge grain oriented electrical steel at the time of development. Initially, the main product was 0.23 mm thick RGH which was adopted not only for wound core, but also for stacked core. The actual sales of 0.20 mm RGH began in 1983 only for wound core use. At around the same time, the loss evaluation system had been introduced in the United States, and as a result, production for North American market increased rapidly.

2.3 Development of Domain Refining Techniques

The measures for iron loss improvement up to this point, such as reduction of impurity contents, improvement of orientation alignment, grain size refinement, gauge reduction, and others had all been metallurgical. The domain refining technique was developed to reduce eddy current loss by a physical method, the concept of which is entirely different from that of the techniques mentioned above. With the new method, domains are refined by the demagnetizing effect of the magnetic poles generated by introducing linear regions of low permeability on the surface of the steel sheet in the direction of substantially right angle to the rolling direction. Although the principle was known previously,[19] the technique had not reached industrial application.

Following the laser irradiation method,[20] which Nippon Steel Corp. first succeeded in industrializing, Kawasaki Steel also began sales of a new domain refined grain oriented electrical steel called "Plasma Core (RGH PJ)" in 1987.[21] The Kawasaki Steel method introduces regions of reduced permeability by irradiating the surface of the steel sheet with a narrowly focused, high-temperature plasma flame. As a feature of this method, it is not necessary to recoat the product after irradiation because the duration of irradiation by the high-energy plasma flame is short, and therefore does not damage the surface coating. Moreover, because the effectiveness of plasma irradiation in reducing iron loss becomes greater as the grain orientation alignment of the material improves, an iron loss improvement of approximately 10% was achieved[22] by applying the plasma irradiation technique to 0.23 mm thick RGH, which has a high B_8, as shown in **Fig. 7**. A disadvantage of this method was that the iron loss improvement effect begins to be lost when the heat treatment temperature of the steel sheet exceeds 500°C, and for this reason, the technique cannot be used with wound core transformers, which require stress relief annealing. Kawasaki Steel therefore undertook the development of a heat-proof domain refining technique capable of withstanding the stress relief annealing at about 800°C.

In 1991, four years after the start of sales of Plasma Core, Kawasaki Steel succeeded in developing a heat-proof domain refining technique in which grooves are formed by an etching method. Sales of this product began the following year under the trade name "RGH PD."[23] In the new method, electrolytic etching is used to form grooves on the surface of the final cold rolled sheet at near right angles to the rolling direction, and domain refinement is achieved by the demagnetizing effect of the magnetic poles formed by the side walls of the grooves. A detailed explanation is presented in a separate report in this issue. The method has the merit of not only being applicable to cores of both the wound and the stacked type, but also, unlike the plasma irradiation method, preventing the induction deteriolation in the relatively low magnetic flux region of 1.7T and under, as

Table 4 Specification and typical magnetic properties of RGH PJ and RGH PD in 1992

Grade	Thickness	Specification		Typical magnetic properties		
		$W_{15/60}$(W/1b)	$W_{17/50}$(W/kg)	$W_{15/60}$(W/1b)	$W_{17/50}$(W/kg)	B_8(T)
23RGHP090	0.23 mm	≦0.38	≦0.90	0.35	0.83	1.90
20RGHPD085	0.20 mm	≦0.36	≦0.85	0.335	0.80	1.87

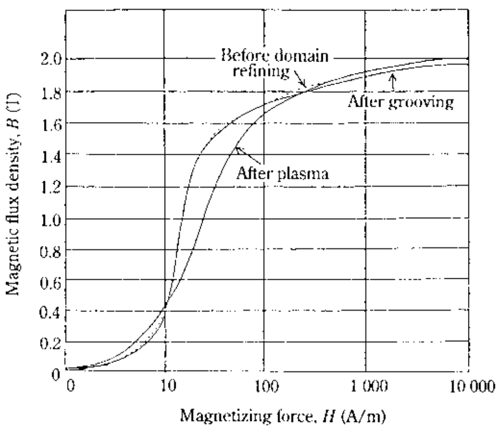

Fig. 8 Magnetization curves of RGH PJ and RGH PD

shown in **Fig. 8**, and it is therefore winning an excellent reputation as an advantageous material for cores in low-noise transformers. **Table 4** shows the typical magnetic properties of RGH PD in comparison with RGH PJ. The iron loss improvement effect of the etching method is substantially the same as that of the plasma method, but the B_8 value is somewhat lower. However, this reduction in B_8 is not due to any change in the degree of grain orientation alignment, but rather originates in the reduction in cross sectional area caused by the grooves. The grooving technique was also applied to New RGH, which features an improved alignment of grain orientation, as will be described in the next chapter, making it possible to realize further improvement in iron loss and thereby meet a higher level of customer requirements.

3 Recent Progress

As discussed above, Kawasaki Steel has developed a series of appropriate products of the world's highest level, including high permeability materials, thin gauge low iron loss materials, and domain refined low iron loss materials, winning a favorable reputation with customers. However, the need for reduced iron loss and reduced noise in grain oriented electrical steel used as the core materials for power transformers is becoming more pressing as energy saving and environmental problems become more urgent. Research and development were therefore conducted in response to these needs, and in particular, the need for reduced iron loss.

A semi-quantitative breakdown of the components of iron loss in 0.23 mm thick RGH (B_8 = 1.91 T) is shown at the left in **Fig. 9**. In the case of $W_{17/50}$, the eddy current loss (0.54 W/kg), which is defined as the value when hysteresis loss (0.34 W/kg) is subtracted from total loss (0.88 W/kg), accounts for approximately 60% of total loss. Approximately 40% of this eddy current loss corresponds to classical eddy current loss, W_{ce}, which is calculated assuming that magnetization changes uniformly; the remaining 60% is abnormal eddy current loss, W_{ae}, which is calculated from local changes in magnetization accompanying 180° domain wall motion.

Eddy current loss can be reduced effectively by reducing the sheet thickness or by increasing electrical resistivity, which is accomplished by increasing the Si content. However, from the viewpoint of production problems, the present sheet thickness and Si content are thought to be near their limits. One method of reducing the remaining W_{ae} is the domain refinement technique. As shown in Fig. 9, W_{ae} is reduced by 0.06 W/kg in RGH PD by domain refinement processing. However, with the present technology, higher levels of domain refinement than this cannot be applied because they would cause a rapid increase in hysteresis loss, which conversely would cause a deterioration in total loss.

The factors comprising hysteresis loss, which is defined as DC iron loss, are of two types, these being factor W_{h1}, which depends on the grain orientation, and factor W_{h2}, which does not show dependence. Because it is not possible to measure the two separately, we will attempt to estimate the amount of loss attributable to each. First, the grain wall meets resistance from the crystal grain boundaries. Because this resistance increases as the deviation in orientation between grains increases, it can be considered to depend mainly on the B_8 value, which is an index of the degree of alignment to the (110) [001] orientation. In the case in which a single grain exists and its orientation also corresponds to the ideal orientation, namely, in the case in which B_8 equals the saturation magnetic flux density, B_s, this resistance W_{h1} can be estimated to disappear, and the value of W_{h1} can therefore be evaluated by investigating the B_8 dependency of iron loss.

Figure 10 shows the relationship between $W_{17/50}$ and B_8 obtained using 0.23 mm thick RGH, which has a wide range of B_8 values. The B_8 values of products which have heat proof domain refining treatment by grooving are expressed by the B_8 values of the materials without domain refining treatment. In Fig. 10, the B_8-related changes in iron loss in the domain refined materials are attributable to changes in the factor W_{h1}, which

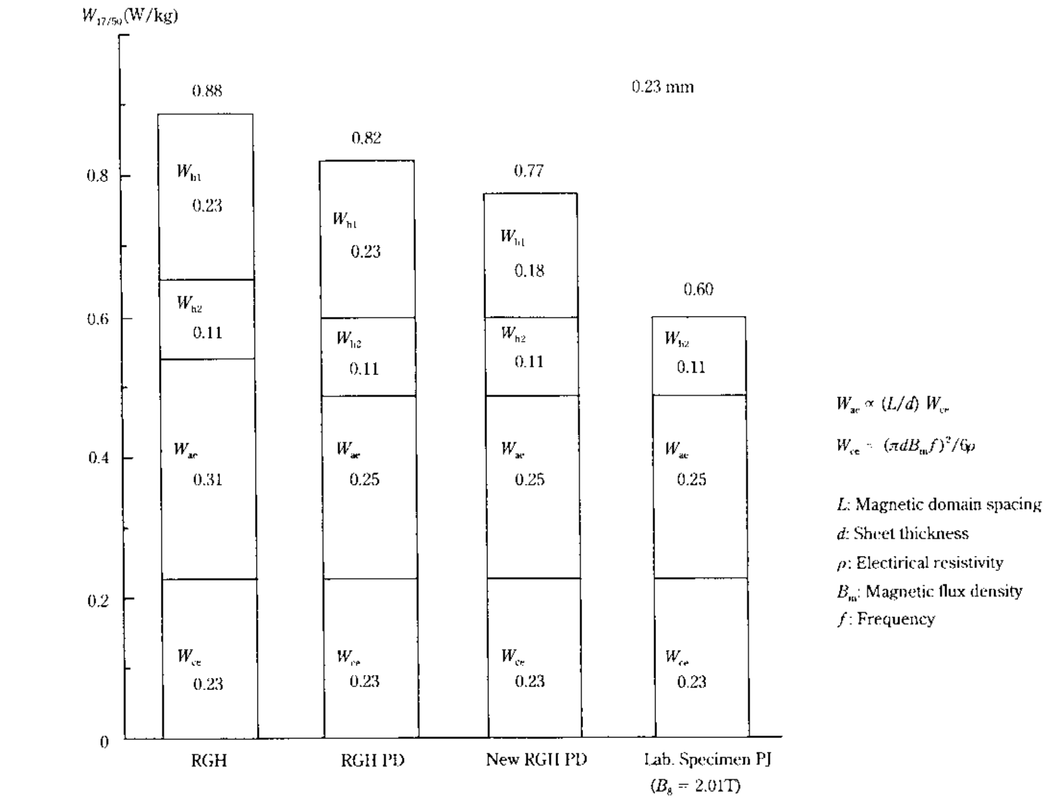

Fig. 9 Iron loss components of RGH, New RGH and lab. specimen with 2.01T of B_8

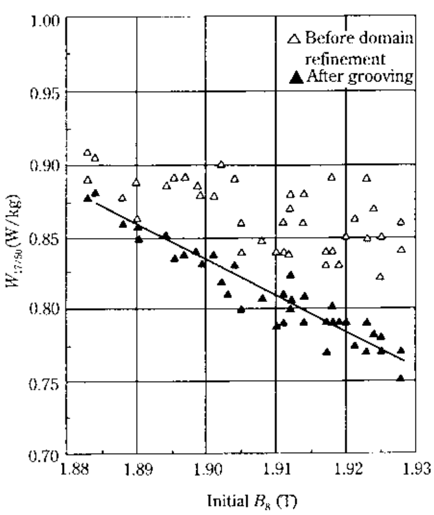

Fig. 10 B_8 dependence of iron loss in RGH with and without domain refinement (0.23 mm)

is dependent on grain orientation, whereas the values of W_{ac}, W_{ce}, and W_{h2}, which are the other factors comprising iron loss, can be thought to be substantially constant. Therefore, W_{h2} can be obtained from hysteresis loss by extrapolating the B_8 values to the ideal condition of B_s = 2.03 T, W_{h1} being equal to 0 on this condition. From this, in the case of 0.23 mm thick RGH, in which B_8 = 1.91 T, hysteresis loss W_{h1}, which is dependent on grain orientation, is found to exist in an amount of W_{h1} = 0.23 W/g, and a value of W_{h2} = 0.11 W/kg is then obtained for the hysteresis loss which is independent of grain orientation.

In the laboratory, Kami et al.[24] prepared a specimen of grain oriented electrical steel which nearly approximated a single grain and showed B_8 = 2.01 T. When given domain refinement treatment by PJ, a value of $W_{17/50}$ = 0.60 W/kg was obtained, as shown at the right side of Fig. 9, and hysteresis loss was 0.12 W/kg. This value, as the hysteresis loss which is dependent on factors other than grain orientation, shows good agreement with the value of 0.11 W/kg that was obtained by extrapolation from B_8 values.

It should also be mentioned that domain wall motion is considered to be affected by resistance caused by roughness at the interface between the substrate steel and the coating film. Nishiike et al.[25] and Nozawa et al.[26] removed the film from product sheets, and then processed the sheets to a mirror-like surface by chemical polishing, etc. Hysteresis loss was measured before and after this processing. With 0.23 mm sheets, values of 0.10–0.14 W/kg were obtained for the reduction in hysteresis loss by mirror polishing.

From a trial calculation of the composition of the hysteresis loss discussed above, it was found that first, increasing the B_8 value, and second, smoothing the surface of the substrate steel, are effective means of reduc-

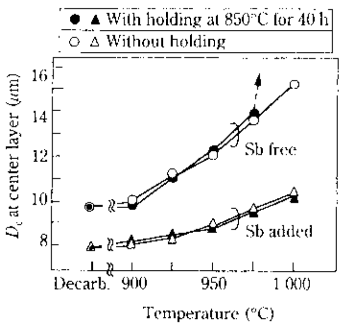

Fig. 11 Change in average primary grain sizes at center and surface part during final annealing

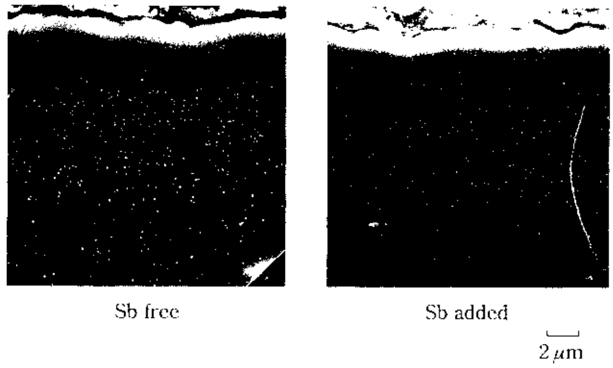

Photo 1 Cross sectional SEM observation of inhibitor precipitation in the vicinity of the surface

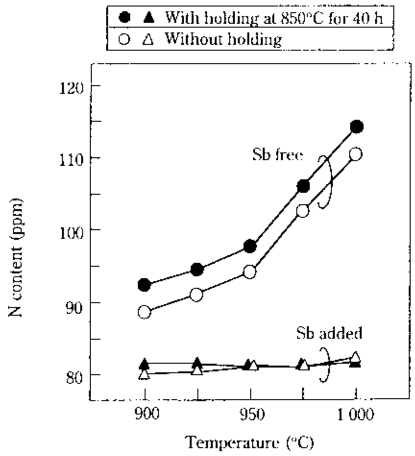

Fig. 12 Change in N content during final annealing

ing iron loss. Increasing the B_8 value as a means of lowering iron loss, namely, improving the alignment of the orientation of secondary recrystallized grains, has been a topic since the earliest stage of the development of grain oriented electrical steel. Moreover, even today, the effectiveness of this method is undiminished. Research in recent years has shown that the following factors are important for improving the orientation alignment of secondary recrystallized grains.

(1) Complex Addition of Inhibitors

Single addition of MnS or MnSe as an inhibitor for restraining normal grain growth of grains other than those of the Goss orientation had been used. However, it has become clear that complex addition, in which nitrides such as AlN, BN, etc. and grain boundary segregating type solute elements such as Sb, Sn, etc. are also added, enhances the inhibiting effect of the former compounds

(2) Suppression of Inhibitor Deterioration during Final Finishing (Secondary Recrystallization) Annealing

It has been discovered[27] that, in the secondary recrystallization process, which occurs in the temperature range of 850–1 100°C, or in the preceding process, precipitates of MnS(Se), AlN, and others, which are inhibitors for restraining normal grain growth, are resolved and dissolved due to the influence of the film on the steel strip surface and the atmosphere between the layers of strip, weakening their effectiveness in inhibiting normal grain growth. Conversely, there is also a phenomenon in which the growth of grains deviating from the Goss orientation is accelerated by additional precipitation. This suggested that suppressing these undesirable influences would be effective in improving the orientation alignment of secondary recrystallized grains.

Based on the key points of research and development mentioned above, Kawasaki Steel developed New RGH, in which the B_8 characteristics of RGH are further improved.[28–30] The features of New RGH include complex precipitates as inhibitors, and in addition, more positive use of the Sb addition effect than in RGH.

Figure 11 summarizes the effect of Sb addition (or the lack thereof) on the average grain size of steel sheets taken out from the furnace during the final finishing annealing process for New RGH before secondary recrystallization (a condition characterized by primary recrystallized grains in which normal grain growth had proceeded to some extent).[31] With the Sb-added steel, grain growth is strongly inhibited in the sheet thickness center layer, which contains a large number of grains deviating from the Goss orientation, but this inhibiting force is weak in the Sb-free steel. **Photo 1** shows the distribution of MnSe in the vicinity of the surface of RGH samples which were taken out from the furnace at 900°C.[32] With the Sb-free steel, MnSe has disappeared in the vicinity of the surface, and its inhibiting effect has been reduced, but with Sb addition, the degree of disappearance is slight. **Figure 12** shows the change in the N content of the steel during secondary recrystallization with New RGH.[31] Without Sb addition, an increase in the N content can be observed. In other words, in contrast to the nitriding which occurs without Sb addition, nitriding is suppressed in Sb-added material. Excessive inhibition of grain growth, which occurs in the surface layer when the N content increases, is undesirable

Table 5 Typical magnetic properties of New RGH

Grade	Thickness	$W_{15/60}$(W/1b)	$W_{17/50}$(W/kg)	B_8(T)
23New RGHPD	0.23 mm	0.34	0.77	1.89
23New RGH	0.23 mm	0.37	0.86	1.93
27New RGHPD	0.27 mm	0.37	0.84	1.89
27New RGH	0.27 mm	0.40	0.93	1.93
30New RGH	0.30 mm	0.45	1.02	1.93
35New RGH	0.35 mm	0.51	1.14	1.93

because it promotes the growth of grains deviating from the Goss orientation. Accordingly, it may be concluded that secondary recrystallized grains with a favorable orientation can be obtained by the Sb addition which has the effect of preventing nitriding.

The development of New RGH has resulted in a material with a high B_8 value when compared with RGH. **Table 5** shows the typical magnetic properties of the respective gauges of New RGH. Iron loss characteristics have also been improved as expected, corresponding to the improved B_8 values. In particular, with heat-proof domain refined material with a thickness of 0.23 mm, it has become possible to supply a product that reaches below the 0.80 W/kg level. A breakdown of the factors in iron loss in New RGH PD was shown in Fig. 9 in comparison with conventional RGH. When compared with RGH PD, New RGH PD shows a reduction in grain orientation-dependent hysteresis loss. With thicker gauge materials of 0.27–0.35 mm, improvement of the B_8 value is particularly related to a reduction in magnetostriction, and has resulted in lower noise in transformers. The new product introductions which appear as a separate feature in this issue include a report on the quality of New RGH and an evaluation of its performance in actual equipment.

4 Outlook for Future

At present, it is still impossible to predict when power generation by natural energy such as wind or solar power will become economically viable, except in some regions with special features, or to predict when the development of revolutionary technologies such as nuclear fusion will be successful. Thus, the increasing demand for electric power must inevitably depend on petroleum and other fossil fuels and nuclear power for some time to come. This means that the cost of electric power can also be expected to rise over the long term. On the other hand, the power transmission and distribution system, which includes the stacked core transformers used in transmission and the stacked and wound core transformers used in distribution, is unlikely to change as long as dream technologies such as the room-temperature superconductor do not become a reality. Partial improvements for higher efficiency will be realized in the transformer itself, but it is difficult to conceive of changes in the fundamental structure. Ultimately, considering the prospects mentioned above, the requirements placed on grain oriented electrical steel as a material for transformer cores will remain basically unchanged from the past, and the need for lower iron loss is expected to remain constant in the future. Moreover, although reduced iron loss is the most basic requirement, it is also unlikely that there will be any weakening in calls for reduced transformer size and lower noise.

To summarize the outlook for future technical development, it is considered possible, as discussed previously, to supply even more outstanding grain oriented electrical steels by optimizing the electrical resistivity, sheet thickness, domain width, grain orientation alignment, roughness of the substrate steel/coating film interface,[33] and other factors which determine the iron loss of grain oriented electrical steel.

5 Conclusion

The history of the development of grain oriented electrical steel has been called the history of improvement in iron loss. Kawasaki Steel has improved iron loss by developing a number of important technologies since it began producing grain oriented electrical steel under the trade name RG in 1961. The main technical milestones include the following:

(1) Development of high permeability grain oriented electrical steel RGH (1973)
(2) Development of thin gauge grain oriented electrical steel RGH (0.23 mm: 1981, 0.20 mm: 1983)
(3) Development of plasma flame irradiation domain refined material RGH PJ (1987)
(4) Development of etched groove heat-proof domain refined material RGH PD (1991)
(5) Development of New RGH with improved magnetic flux density (1994)

Among these, items (4) and (5) are noteworthy as examples of recent progress. Heat-proof domain refined material can be applied in cores of either the stacked or the wound type, has excellent low magnetic field characteristics, and is suitable for noise reduction. New RGH PD with a thickness of 0.23 mm shows low iron loss of 0.77 W/kg and can contribute to iron loss reduction and reduced size in power transformers, while heavier gauge New RGH with thicknesses of 0.27–0.35 mm, possesses high permeability, with a B_8 value of 1.93 T, making it possible to realize lower noise in power transformers by the use of this material.

Although the grain oriented electrical steel of today is already a product with an extremely high degree of completion, there is still considered to be room for improvement by bringing each of the element technologies closer to its ideal condition. By responding to the needs of customers, centering on lower iron loss, the authors hope to contribute to a more energy-efficient society in the future.

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