KAWASAKI STEEL TECHNICAL REPORT

No.39 (October 1998)

Electrical Steel

History and Recent Development of Non-Oriented Electrical Steel in Kawasaki Steel

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History and Recent Development of Non-Oriented Electrical Steel in Kawasaki Steel*


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Since the first production of cold rolled non-oriented steel strip in 1954, Kawasaki Steel has developed various kinds of electrical steels, and has established mass production techniques, facilities and systems for producing non-oriented electrical steels having not only excellent magnetic properties but also good punchability, weldability, strict gauge accuracy and appropriate mechanical properties. Recently, new products such as 50RM230 of the lowest iron loss, RP series of high permeability, and RMA series of low iron loss, secured after SRA (stress relief annealing), were developed. These are expected to meet customers' requirements from the viewpoint of energy saving and efficiency improvement of motors for home appliances of late years.

1 Introduction

Non-oriented electrical steel is used as the core material of rotating machinery, mainly such as generators and motors, because its magnetic properties are not biased in any specific direction. It is also widely used as core material for small electric power transformers and other stationary equipment because its punchability and other kinds of workability are superior to those of grain oriented electrical steel. Thus, non-oriented electrical steel is an important material whose progress has made a large contribution to the development of electrical machinery, and particularly to power conservation through improved efficiency. One feature of non-oriented electrical steel is its wide range of applications, from large rotating machinery in which low iron loss is necessary to small electrical devices in which high permeability is required. Corresponding to these varied uses, non-oriented electrical steels are manufactured in many grades, from high grade non-oriented electrical steel strip with an Si content of approximately 3% to low grade products containing virtually no Si. These steels are required to provide a diverse range of properties, including magnetic properties, strict gauge accuracy punchability, electrical insulation properties by coating, corrosion resistance, mechanical properties, weldability, and others.

* Originally published in *Kawasaki Steel Giho*, **29**(1997)3, 136–141

The production of electrical steel at Kawasaki Steel began with hot rolled Si steel in the early 1930s. Production of cold rolled non-oriented Si steel strip (coils 400 mm in width) began in 1954 under the name RM Core. From 1959 onward, a stable supply system, in terms of both quality and quantity, was established for the production of wide products and various grades. Moreover, in response to new trends such as automation, higher efficiency in production and miniaturization of electrical machinery and tools, Kawasaki Steel also have prepared new products with special features, including 50RM230, which is the highest grade of non-oriented electrical steel, the RP series of high permeability, and the RAM series of low iron loss after stress relief annealing.

In the present paper, a short history in the development of these non-oriented electrical steels and recent progress at Kawasaki Steel are described.

2 History of Development of Non-Oriented Electrical Steel

2.1 Transition from Hot Rolled to Cold Rolled Steel Strip

Initially, hot rolled electrical steel in cut sheet form was produced using the pull-over mill. This was the period when the strip mill at the plate works of Kawasaki Dockyard Co., Ltd. (later renamed Fukiai Works of Kawasaki Steel), which was established for the domestic production of flat products, survived the financial panic of 1927 and eventually became a healthy operation. However, following the Second World War, the quality of flat products declined remarkably due to poorer raw materials and other factors. Research on electrical steel started with the aim of improving this situation, and this became an opportunity for promoting the development of electrical steel, which had lagged behind the United States and Europe. During this period, the production of steel sheet worldwide was characterized by attempts to move from cut sheet to high grade, high productivity steel coil. Likewise, Kawasaki Steel constructed a semi-continuous hot rolling mill at Nishinomiya Works in 1951. Although this was a narrow width strip mill, the hot coils rolled on this line were processed by a reversing type cold rolling mill, and the changeover from cut sheets to coils was realized. Following the war, the steelmaking process had depended on the electric furnace, but in 1954, the Fukiai Works open hearth furnace was started up, and at the same time, a high temperature hydrogen annealing technology was established. These various technologies enabled the company to develop a hot rolled electrical steel product of the highest grade, T90 ($W_{10/50} \leqq 0.9$ W/kg), which was equal to American and European products, and began production of a cold rolled electrical steel called RM Core.

Because the application of an insulation coating is indispensable with cold rolled steel sheets, which lack a surface oxidation layer, the development of coating compositions and continuous coating technology were also pursued in parallel, and coat-and-bake type phosphate coating called "D Coat" was completed in 1958.[1] In 1966, the mass production system for cold rolled coils was established, bringing an end to the history of hot rolled electrical steel production at Kawasaki Steel, which had spanned more than 30 years.

2.2 Development of Mass Production of Wide Cold Rolled Electrical Steel Strip

Kawasaki Steel's Chiba Works was opened in 1951 with the aim of becoming the world's most modern steel works. A blast furnace and open hearth furnace were constructed first, followed by a hot strip mill and cold strip mill. In 1958, with the completion of these facilities, the construction of a full-scale electrical steel shop was started at Fukiai Works with the premise of using wide hot coils produced at Chiba Works. The following year, in 1959, a continuous annealing line was constructed at the Fukiai Works electrical steel shop, and Fukiai Works began producing non-oriented electrical steel strip in wide width. Production of RM Core began with the 50RM470-50RM600 "RM 18-23," and a succession of low Si products for the home appliance industry and high Si products for large rotating machinery were developed. The 1960s saw remarkable growth in the production of electrical devices such as home appliances, and high induction material gradually came to be required as core material for the small motors used in such products, although iron loss was somewhat high in such materials. In response, 50RM1300 "RM40" was developed in 1961, followed by RK Core, an electrical steel sheet with a low Si content, in 1963. In later years, RK Core became a large-volume product in the form of 50RM1000 "RM50" and 50RM1300 "RM60."

During the same period, Kawasaki Steel also responded to the demand for a high induction, low cost material for small motors by beginning the development of a cold rolled product for delivery in a semi-processed state, and began sales of Hyper Core "HPS," which possessed higher induction and offered iron loss after annealing in the 50RM700 "RM30" class. Semi-processed products, which assume that stress relief annealing will be performed by the customer, enjoyed strong demand in the United States, where natural gas could be procured at an economical price, and as a result, the cost of annealing was low. Basically, this type of product was given a small amount of strain by skin-pass rolling after final annealing, and hysteresis loss was reduced by the grain coarsening caused by strain induced grain growth during stress relief annealing by the customer. Thus, it was a feature of this product that, simultaneously with low iron loss, it also showed high induction because its Si content was held to a low level. In 1982, Kawasaki Steel succeeded in developing another semi-processed product, Y Core, with markedly higher magnetic permeability ($\mu \geqq 4\,000$ at 1.5T). This material showed particularly outstanding magnetic properties in the rolling direction as a result of texture control by Sb addition and was highly evaluated as a material for EI cores. As a material for motor cores, HPS-0 was developed in 1985 in response to strong new demand for lower iron loss rather than higher magnetic permeability.

In the development of high grade non-oriented electrical steel for use in large rotating machinery, it became possible to produce a 50RM330 "RM11" in 1962, which was followed by the development of 50RM310 " RM10" in 1966 and 50RM290 "RM9" in 1970. These high grade products were used mainly in the yokes of generators, and contributed to energy saving by making it possible to improve generating efficiency.

Initially, all non-oriented electrical steels produced by Kawasaki Steel were coated with the previously mentioned D Coat. Because D Coat provided extremely good heat resistance and corrosion resistance, it enjoyed a favorable reputation with customers and made a large contribution to the rapid acceptance of RM Core. This technology is widely used even today, and was also licensed to a German chemical manufacturer. Thereafter, in response to stronger requirements for improved punchability, P Coat,[2] which is advantageous for punchability, and C Coat, which markedly improves punchability by adding an organic resin, were developed. In 1974, a semi-organic coating, A1 Coat,[3] was developed as a general-purpose coating with excellent total properties, including heat resistance, punchability, weldability, and others, and has continued to improve its properties up to the present day.

2.3 Development of Higher Grade and More Diverse Products

As mentioned previously, the product groupings in non-oriented electrical steel was sharply differentiated into low iron loss products for large rotating machinery and high induction products for small motors. Although these groupings had been established in the Japanese Industrial Standard (JIS C 2552), Kawasaki Steel went beyond this framework and positively expanded its development of high function materials which conformed more closely to the requirements of customers.

The development of a material of the highest standard for low iron loss owed a great debt to progress in technologies for achieving high purity, beginning with desulfurization in the steelmaking process. In 1978, 50RM270 "RM8" was developed,[4] followed in 1983 by the development 50RM250 "RM7," using high purity steel with extremely low levels of S, O, N, and other impurities as the base material.[5-7] Thereafter, a product with even lower iron loss, 50RM230 "RM6," was successfully developed. **Figure 1** shows the history of iron loss improvement in non-oriented electrical steel at Kawasaki Steel.

Initially, higher induction was also achieved as a result of lowering Si content. However, in contrast to the low iron loss steels, the high magnetic flux density steels in the RP series, which show higher B_{50} values of 0.02–0.03T at the same Si content, were commercialized in 1985 by applying texture control techniques. **Figure 2** shows the history of flux density improvement in non-oriented electrical steel at Kawasaki Steel.

Steels with low iron loss after stress relief annealing were also developed. In the field of compressor motors and similar devices, because importance is attached to low iron loss as well as to reduced size, stress relief annealing is performed after the sheet is punched. A material which simultaneously provides both high induction and low iron loss after stress relief annealing was therefore developed to satisfy the requirements for this usage, and was commercialized as the RMA series. At present, this product line has been commercialized up to RMA350, which is a product of the highest grade. The relationship between iron loss and magnetic flux density in this product group is shown in **Fig. 3**.

High-grade semi-processed products, which are shipped mainly to North American market, have also earned a favorable reputation for their excellent properties, as mentioned earlier in this paper. In particular, the production technology for high-grade semi-processed products using Sb or Sn addition[8,9] has been licensed to several steel mills in the United States.

In the production of high quality electrical steel, excellent facilities and an integrated quality control system are indispensable. For this purpose, Kawasaki Steel shifted production from Fukiai Works, which had been responsible for the cold rolling process, to Mizushima Works, enabling a large scale production of high quality non-oriented electrical steel using state-of-the-art equipment and a total quality control system.

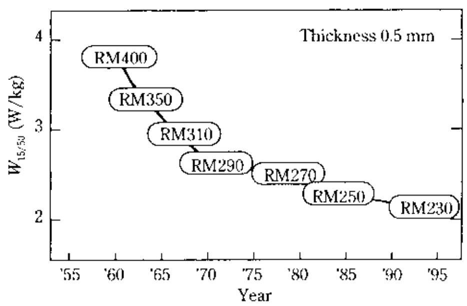


Fig. 1 Improvement of iron loss in the best grade of RM

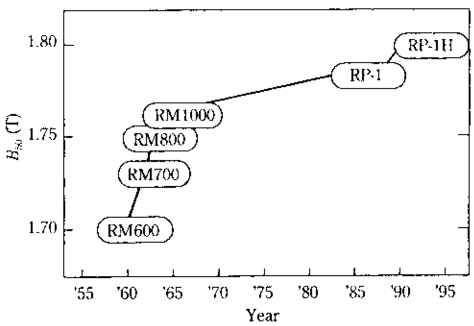


Fig. 2 Improvement of flux density in RM

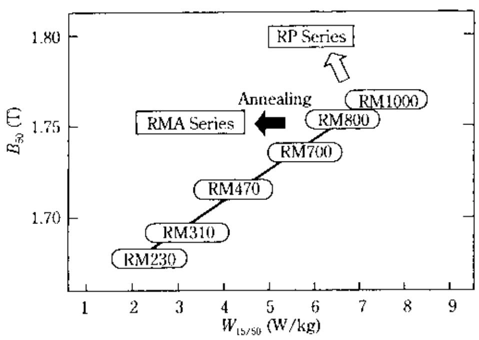


Fig. 3 Relation between magnetic flux density and iron loss (the values of RMA series were measured after stress relief annealing)

3 Recent Progress in Non-Oriented Electrical Steel

3.1 Factors Influencing Magnetic Properties

Various properties are required in non-oriented electrical steel, depending on the application. Among these, low iron loss is required for the highest grade products, which are used in large rotating machinery, and high induction is required for products used in devices in which small size is demanded. Moreover, to achieve low iron loss in materials which are used after stress relief annealing by the customer, a good grain growth property is necessary. To satisfy such diverse requirements, sheets are produced with optimum control of the metallurgical factors which influence magnetic properties. An outline of these factors is presented below.

3.1.1 Si, Al contents and sheet thickness

Iron loss can be divided into hysteresis loss and eddy current loss, and the eddy current loss can be further divided into classical eddy current loss and anomalous eddy current loss in which the domain structure is taken into account. Classical eddy current loss, W_e, is expressed by the following equation.

$$W_e = k(tfB)^2/\rho$$

Here, k: constant, t: sheet thickness, f: frequency: B: magnetic flux density, and ρ: resistivity.

As the amount of Si or Al addition increases, the resistivity, ρ, of the sheet also increases, and iron loss decreases in accordance with the equation shown above. On the other hand, the addition of these elements reduces the saturation magnetization of the material, and thus reduces magnetic flux density. For this reason, Si and Al contents are decided so as to satisfy the target magnetic properties. Generally, the amount of addition is larger in higher grade products, in which lower iron loss is required. Reducing the sheet thickness is also effective in reducing iron loss, as is clear from the equation shown above. Gauge reduction might be called the ideal method of improving magnetic properties because it causes virtually no deterioration in magnetic flux density brings about an improvement of high frequency iron loss. However, there are practical limits to the applicability of gauge reduction, because it causes the increase of labour cost for stacking motor cores and EI cores and deteriorates productivity.

3.1.2 Grain size

Among the components of iron loss in non-oriented electrical steel, eddy current loss increases and hysteresis loss decreases as the grain diameter increases. This is because the domain width increases, resulting in greater anomalous eddy current loss, as the grain diameter increases, whereas larger grain diameters reduce the area of the grain boundary, which impedes domain wall motion, and thereby reduce hysteresis loss. Thus, there is an optimum grain diameter for minimizing iron loss, which is the sum of eddy current loss and hysteresis loss. Further, because hysteresis loss is also influenced by the presence of inclusions, the texture, and other factors, it is also necessary to optimize these conditions. With high Si steel, the optimum grain diameter is relatively large, at around 150 μm, as shown in **Fig. 4**. Therefore, material control which adequately promotes grain growth in a relatively short annealing time is necessary in industrial operations. In particular, it is important to minimize the content of fine precipitates and inclusions, which impede grain growth.

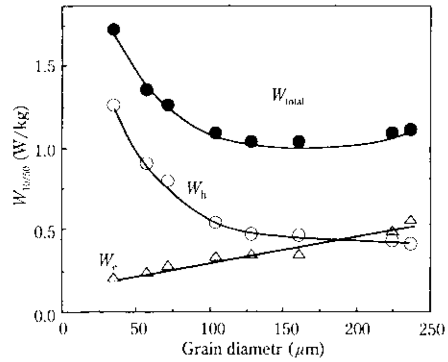


Fig. 4 Influence of grain diameter on hysteresis loss, W_h, eddy current loss, W_e and total iron loss, W_{total}

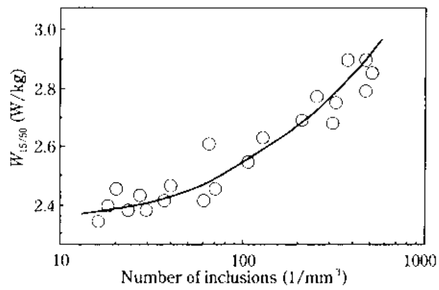


Fig. 5 Effect of inclusions on iron loss (thickness 0.5 mm)

3.1.3 Inclusions

Sulfides, oxides, nitrides, and other precipitates and inclusions exist in steel. The diameter of inclusions ranges from approximately less than 0.1 μm to several 10 μm. These inclusions deteriorate hysteresis loss by impeding grain growth, and in addition, they also directly deteriorate magnetic properties. This is because domain wall motion is hindered by the inclusions themselves or by the peripheral lancet domains which are formed when inclusions cause a reduction in magnetostatic energy. **Figure 5** shows an example of the reduction of iron loss when the number of inclusions in the steel is reduced.[7] **Photo 1** is an example showing the

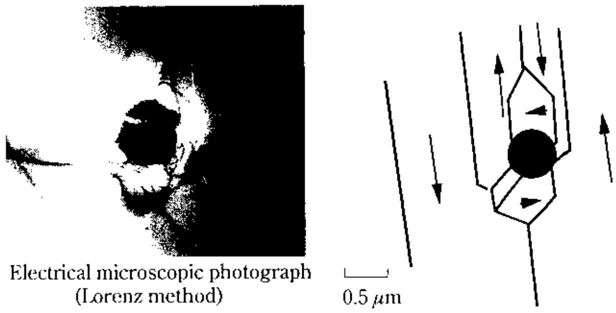


Photo 1 Magnetic domain in the vicinity of inclusion observed by Lorenz TEM method

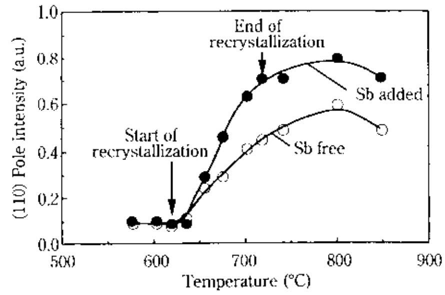


Fig. 7 Change in (110) pole intensities during recrystallization and grain growth

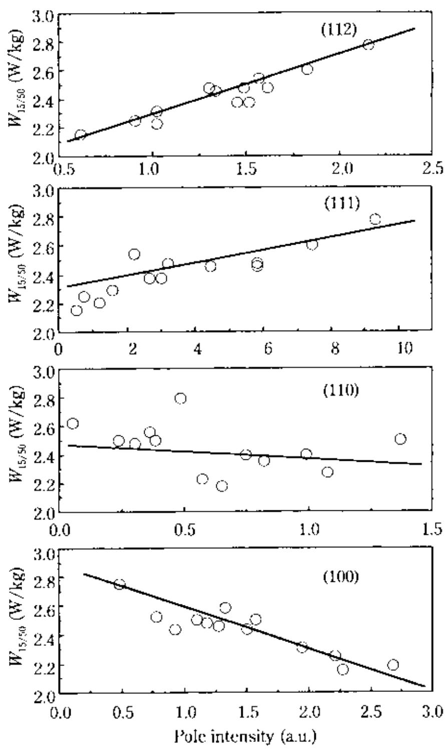


Fig. 6 Relationship between pole intensity and iron loss

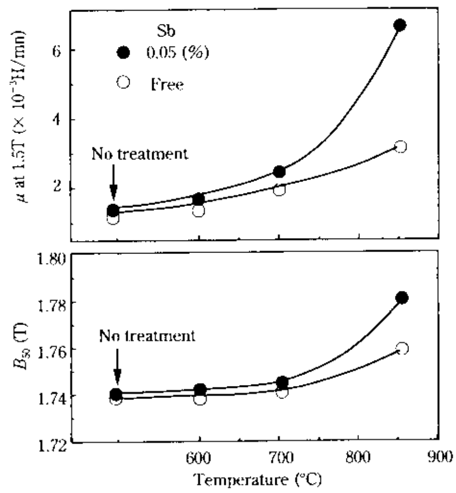


Fig. 8 Effect of Sb addition and hot band annealing on magnetic properties

effect of an inclusion on the domain structure. Reducing the absolute amount of inclusions is a matter of the first importance. However, it is also important to control the size and distribution of inclusions to the morphology, minimizing the bad effect. Assuming the absolute amount of inclusions is the same, the negative effect of such inclusions on grain growth and domain wall motion is minimized when the inclusions are made as coarse as possible. However, because excessive inclusion size causes deterioration of the texture (discussed in the next section), resulting in increased iron loss, the balance of these characteristics becomes important.

3.1.4 Texture

The condition of having a so-called preferential orientation, in which grains are aligned in a particular direction, is called texture. The magnetic properties of electrical steels are strongly dependent on their textures. As shown in **Fig. 6**, it is known that iron loss decreases as the (100) and (110) pole intensity increases; conversely, iron loss increases as the (112) and (111) pole intensities become stronger.[7] This is due to the fact that electrical steels have strong magnetic anisotropy, being most easily magnetized in the direction of the [100] grain axis and most difficult to magnetize in the [111] direction. More specifically, this is because two [100] axes exist in the (100) plane and one [100] axis exists in the (110) plane, whereas there are no [100] axes in the (111) and (112) planes. Further, it has been found that texture can be improved remarkably by the addition of Sb,[10,11] and Sb is therefore used to improve magnetic properties.[12] By adding Sb, the useful (110) orientation is increased and the undesirable (111) orientation is suppressed (**Fig. 7, 8**).[13]

The ideal texture of non-oriented electrical steel varies depending on its application. For motors, a uniform (100) [0 vw] texture with no anisotropy, or the so-called isotropic texture, is ideal. On the other hand, for EI cores, ballast cores, and other stationary equipment, the ideal is (100)[001], because the magnetic flux can flow in the rolling direction and at right angles to the rolling direction. At present, however, this texture can be obtained only by extremely special manufacturing methods, and has not yet reached the point where it can be adopted in electrical steels for the commercial market. For this reason, texture control to reduce the (111), (112) planes, which are disadvantageous for magnetic properties, is generally important.

3.2 Product Development

Precise control of the process conditions based on the principles discussed above has made it possible to develop a variety of non-oriented electrical steel products, as described in the following.

(1) Development of Highest Grade Non-Oriented Electrical Steel Sheet 50RM230[12,14]

High purity in the molten steel is a matter of the first importance for the development of the highest grade of steel sheet. In addition, the elements Si and Al, which increase resistivity, are added within the range allowed by cold rolling technologies. In 1978, 50RM270 was developed using high purity steel as the material, and in 1982, 50RM250 was developed by applying inclusion shape control, in which REM are added to low-S steel. The application of high purification technology, inclusion dispersion control, texture control, and other techniques has made it possible to develop and supply 50RM230 ($W_{15/50} \leqq 2.3$ W/kg) and 35RM210 ($W_{15/50} \leqq 2.1$ W/kg), which are at present the world's highest level steels in their class.

(2) Development of High Induction RP Series[13,15]

The high induction RP series was developed to respond to the heightened demand for reduced size and improved efficiency in equipment in recent years. The Si content decreases in the order RP1, RP2, RP3. The best grade RP-1H, which displays the highest induction, satisfies $B_{50} < 1.79$T. These steel sheets are produced using advanced texture control technology.

(3) Development of RMA Series with Low Iron Loss after Stress Relief Annealing[16,17]

The RMA series, which shows particularly excellent grain growth during annealing, was developed as a series of steel sheets with effectively reduced iron loss after stress relief annealing by the customer while maintaining magnetic flux density. Improvement of the grain growth property can be obtained by inclusion morphology control. A variety of products have been developed in this series, from RMA600 ($W_{15/50} \leqq 6.0$ W/kg) to RMA350 ($W_{15/50} \leqq 3.5$ W/kg).

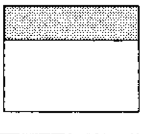
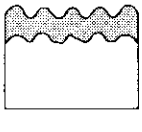
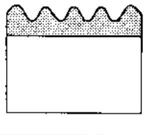
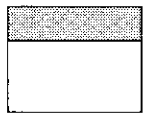
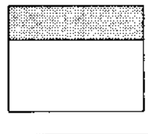
3.3 Progress in Coatings

Because electrical steel is used by lamination after punching or shearing into various shapes, a variety of characteristics are required for the coating which is applied to the sheet surface, depending on the processing method and application. **Table 1** shows the characteristics of the coating used on Kawasaki Steel's RM sheets. The semi-organic Al Coat, which is a general purpose coating, has excellent total characteristics, and at present is used both in the greatest quantity and most generally. The A2 and A3 Coat, in which a dull surface is formed either on the steel sheet surface or on the coating itself, are also semi-organic coating with improved weldability. The inorganic D Coat is particularly excellent in heat resistance and weldability.[3]

B Coat, which is an organic adhesive resin capable of heat bonding, was developed and commercialized for applications in which clamping, welding, and other methods of joining cannot be applied, and for applications which require airtightness between stacked sheets.

Thus, Kawasaki Steel has developed coatings which possess various characteristics, and has also accumu-

Table 1 Characteristics of insulating coatings for RM-core

Coating	A1	A2	A3	D	B
Composition	Inorganic with some organic			Inorganic	Organic
Cross section					
Feature	General use	Dull surface	Dull coating	Phosphate coating	Adhesion coating
Lamination factor	◎	△	△	◎	△
Interlaminar resistance	○	○	◎	○	◎
Punchability	○	○	○	△	◎
Weldability	△	○	○	◎	△
Heat resistance	○	○	○	◎	×

◎ Excellent ○ Good △ Not good × Poor

lated and organized data on the properties of these respective coatings so as to be useful in the optimum selection by the customer.

3.4 Optimization of Mechanical Properties[16)]

Non-oriented steel sheets must provide mechanical properties suited to the customer's processing methods, for example, ensuring punchability and punching accuracy, ensuring clamping strength, etc. Hardness and sheet microstructure are optimized for individual applications with special importance attached to uniformity of the mechanical properties in order to meet the requirements of process automation.

3.5 Improvement of Gauge Accuracy

Particularly strict gauge accuracy over the full length and full width of coils is required for non-oriented electrical steels. Improved gauge accuracy in the longitudinal direction has been achieved to an accuracy of $\leqq 2.5$ μm even in the non-steady regions of line acceleration and deceleration by developing an all-stand gauge and tension control system for the cold rolling mill.[18)] Transverse gauge accuracy has been significantly improved by applying the one-side tapered work roll shift rolling technology,[18)] which was firstly developed by Kawasaki Steel in the world.

3.6 Quality Assurance

In order to assure the quality of the manufactured steel strip over its full length, an on-line continuous iron loss measurement device and a surface defect detection device were installed to make doubly sure of quality assurance over the full length and width. Certification under ISO 9001 was received in June 1994.

3.7 Research on Evaluating Methods in Actual Equipment

In evaluating the properties of non-oriented electrical steel sheets, more information can be obtained by measuring the properties of an actual device in which the electrical steel is used than by the Epstein test, as specified in JIS 2550. It is important to feed back this information into the product development process.

Knowledge obtained at Kawasaki Steel by developing a 600 W single phase motor[19)] and 400 W 3-phase, 6-pole inverter motor evaluation device[20)] will be presented here.

Figure 9[19)] shows the effect of the Si + Al content of the core material on iron loss, copper loss, and total loss in the single phase motor. In this motor, the flux density of the stator yoke is 1.33, and that of the teeth is 1.50T. With this kind of design, motor iron loss is reduced because eddy current loss decreases as the Si + Al content of the core material increases. However, motor copper loss increases because permeability decreases. As a result, there exists an optimum Si + Al content for minimizing total loss. Moreover, because the optimum Si + Al content decreases as the designed flux density increases, it is possible that low Si + Al material may be advantageous for reducing motor size.

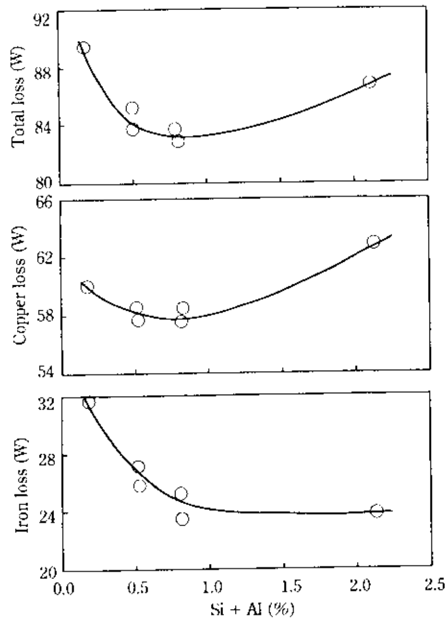


Fig. 9 Effects of Si + Al contents of core material on iron loss, copper loss and total loss of single phase induction motor

Regarding the 400 W inverter motor, the investigated results of the effect of material Si content, thickness, and PWM frequency, and the use of stress relief annealing on motor efficiency are presented in the separate paper in this issue.[20)]

4 Conclusion

During the 35 years since the wide cold rolled electrical steel sheets were commarcialy produced, Kawasaki Steel has improved the magnetic properties of its non-oriented electrical steels and developed products that respond to diverse needs. In particular, lower iron loss and higher permeability are constantly required, and uninterrupted efforts have therefore been paid to improve these properties. To obtain good workability and other characteristics, optimum control of mechanical properties and the dimensional accuracy of sheets are secured, and coatings with a variety of features have been developed and improved. A large number of evaluation methods have also been developed to verify the properties of electrical steels.

In recent years, Kawasaki Steel has developed new products with special features, such as the highest grade non-oriented electrical steel, RM230, high permeability non-oriented electrical steel, RP-1H, and non-oriented electrical steel with low iron loss after stress relief annealing, RMA350, and high function coatings for general purpose, A1 Coat, B Coat for bonding lamination, and others.

In the future, the applications of electrical steel sheets will become more diverse, and from the viewpoint of energy conservation, higher efficiency will be required not only in generators and other large equipment, but also in the small motors and small stationary devices which are used in home appliances. Kawasaki Steel is therefore resolved to continue the efforts to develop products which respond to the demands of customers.

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