

# Recent Development of Grain-Oriented Electrical Steel in JFE Steel<sup>†</sup>

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## Abstract:

*JFE Steel has been seeking for low iron loss technologies of grain oriented electrical steels since starting the production of grain oriented electrical steels in 1959. A low iron loss grain oriented electrical steel “JGSD<sup>TM</sup>” was developed in 1994, and then a low iron loss grain oriented electrical steel for stacked core transformers “JGSE<sup>TM</sup>” has been recently developed. These materials are making a substantial contribution to global society through energy conservation of transformers.*

## 1. Introduction

Grain-oriented electrical steel is used mainly as a core material for transformers, and its iron loss properties have a large effect on transformer energy efficiency. Therefore, JFE Steel has vigorously promoted technical development of low iron loss technologies for grain oriented electrical steel.

This paper describes the history of development of grain-oriented electrical steel at JFE Steel and the company’s product line-up. The level of magnetic properties achieved in recent highest grade products is also introduced, together with the characteristics of transformers using those products.

## 2. History of Development of Grain-Oriented Electrical Steel

### 2.1 Needs of Times for Energy Saving

The rise in social needs for energy saving in trans-

formers begins with the 1st Oil Crisis in 1973. More recently, strict regulations have been applied to transformers from the viewpoint of preventing global climate change; these include the Top Runner Program in Japan, the Department of Energy (DOE) regulations in the United States and the Ecodesign Directive in Europe.

In Japan’s Law Concerning the Rational Use of Energy, equipment in which improvement of energy consumption efficiency is deemed necessary is designated as “specified equipment.” The “target fiscal year,” which is the fiscal year when regulations take effect, and “energy consumption efficiency,” which is the standard value to be achieved, are provided in “criteria, etc. for judgment of improvement of performance of specified equipment by manufacturers and others,” and manufacturers and importers of the specified equipment concerned are obligated to make efforts to achieve those standards. In the “1st judgment standard,” which was announced in December 2002, oil-filled transformers were subject to regulations from fiscal year (FY) 2006 and molded transformers were subject to regulations from FY 2007. Under these regulations, transformers conforming to the “1st judgment standard” (Top Runner transformers) realized an energy saving of 32.8% in “energy consumption efficiency (in case of transformers, total iron loss; unit: W (watt))” in comparison with the former products. Low iron loss in grain oriented electrical steel is indispensable for achieving high efficiency in transformers, and improvement of grain oriented electrical steel made a large contribution to the Top Runner transformers. Following the “1st judgment standard,” further increases in the efficiency of iron cores and winding materials and improvement of processing tech-

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nologies were studied, and in March 2012, the “2nd judgment standard” was announced. The total iron loss of transformers conforming to the “2nd Judgment Standard” (Top Runner transformers 2014) achieved a 12.5% improvement in comparison with transformers conforming to the “1st Judgment Standard” and an improvement of 39.4% in comparison with the former products manufactured before the “1st Judgment Standard,” which account for the majority of transformers currently in operation. This has made an important contribution to both protection of the global environment and energy conservation. Grain oriented electrical steel with further improved performance was also used in Top Runner transformers 2014, contributing to energy conservation and suppression of increased external size and mass of the equipment.

Introduction of Top Runner transformers has had an extremely large effect in reducing CO<sub>2</sub>. As of the end of FY 2012, cumulative shipments of Top Runner transformers by transformer companies belonging to the Japan Electrical Manufacturers’ Association (JEMA) were 535 thousands units with a total capacity of 116 GVA. The effect of reduced energy consumption on the environment calculated from these actual shipment results is 1 800 million kilowatt hours per year, and the CO<sub>2</sub> reduction effect reaches 1 million tons per year<sup>1,2)</sup>.

In order to respond to the needs of society for energy saving in transformers and reduction of CO<sub>2</sub> emissions as described above, JFE Steel has consistently pursued technologies for realizing low iron loss in grain oriented electrical steel.

## 2.2 Features of Grain-Oriented Electrical Steel and Principle of Iron Loss Improvement

The features of grain-oriented electrical steel are shown schematically in **Fig. 1**. Grain-oriented electrical steel is a type of steel sheet with a sheet thickness of 0.20–0.35 mm and a Si content of approximately 3%. It consists of crystal grains with a near {110} <001> orientation, which is termed the Goss orientation, and the axis of easy magnetization (<001> orientation) is highly oriented in the rolling direction. For this reason, grain oriented electrical steel has extremely high magnetic properties in the rolling direction.

A coating with an electrical insulating property, called an insulating coating, is provided on the surface of grain-oriented electrical steel. This insulating coating also acts to impart tension to the steel sheet, which contributes to improvement of iron loss characteristics.

The magnetic features of grain-oriented electrical steel are shown schematically in **Fig. 2**. Grain-oriented electrical steel consists of very small regions, called magnetic domains, which have the same spontaneous magnetization direction. The boundary between two

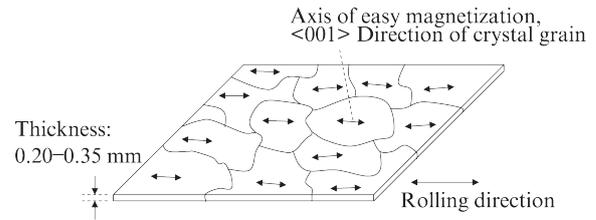


Fig. 1 Schematic diagram of crystallographic features of grain oriented electrical steel sheet

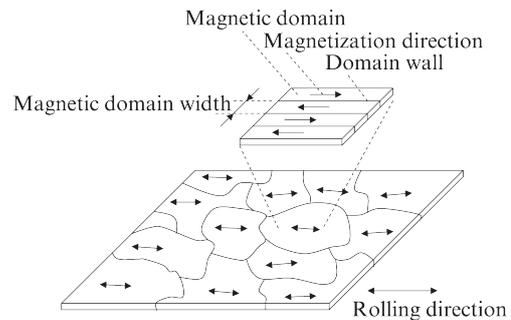


Fig. 2 Schematic diagram of magnetic features of grain oriented electrical steel sheet

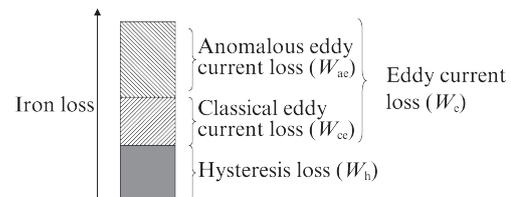


Fig. 3 Schematic diagram of iron loss of grain oriented electrical steel sheet

domains is called a domain wall.

An example of the composition of the iron loss of grain oriented electrical steel sheets is shown in **Fig. 3**. The iron loss of grain oriented electrical steel consists of hysteresis loss ( $W_h$ ) and eddy current loss ( $W_e$ ), and eddy current loss further comprises classical eddy current loss ( $W_{ce}$ ) and anomalous eddy current loss ( $W_{ae}$ ).

Hysteresis loss ( $W_h$ ) is energy loss caused by the irreversibility of domain wall motion. Because fine precipitates and inclusions in a steel sheet impede domain wall motion, hysteresis loss increases by the irreversibility of domain wall motion. Therefore, elements such as C, N, O, S, and others which form precipitates and inclusions are reduced to the ultimate limit. On the other hand, iron crystals have the feature of being magnetized most easily in the direction of the axis of easy magnetization (<001> direction), and hysteresis loss decreases as the angle between the direction of magnetization and the <001> direction becomes smaller. Thus, increasing the alignment of the crystal orientation is effective for reducing hysteresis loss.

Eddy current loss ( $W_e$ ) is Joule heat which is caused by the eddy currents generated in a steel sheet by the action of electromagnetic induction when the steel sheet is magnetized by an alternating current.

Classical eddy current loss ( $W_{ce}$ ) is the eddy current loss when the magnetization in a material changes uniformly, and can be considered by Eq. (1).

$$W_{ce} = K_1 B_m^2 d^2 f^2 / \rho \dots \dots \dots (1)$$

Where,  $K_1$ : Constant,  $B_m$ : Maximum magnetic flux density,  $d$ : Sheet thickness,  $f$ : Frequency,  $\rho$ : Electrical resistance of steel sheet.

From this equation, it can be understood that reducing the sheet thickness and increasing the electrical resistance of a steel sheet are effective for reducing classical eddy current loss. The Si content which is added to electrical steel increases the resistance of the sheet and thereby acts to reduce classical eddy current loss.

Excess eddy current loss ( $W_{ae}$ ) is caused by domain wall motion, and can be expressed by Eq. (2).

$$W_{ae} = K_2 B_s^2 V^2 d / \rho \dots \dots \dots (2)$$

Where,  $K_2$ : Constant,  $B_s$ : Saturation magnetic flux density,  $V$ : Velocity of domain wall motion.

Reducing the magnetic domain width is effective for reducing excess eddy current loss ( $W_{ae}$ ). The velocity of motion of the domain walls in the alternating current magnetization process is reduced by decreasing the width of the domains, in other words, by increasing the number of domain walls, and as a result, excess eddy current loss is also reduced. It is known that refining the grain size and increasing the tensile stress which the insulating film gives to a steel sheet are effective for reducing magnetic domain width. As methods of magnetic domain refinement, which physically reduces the magnetic domain width, the method of introducing local strain in the steel sheet and the method of forming grooves in the steel sheet surface are known. The method of introducing local strain in the sheet is called non-heat resistant domain refinement because strain is recovered by annealing at 500°C or higher and the magnetic domain refinement effect is lost. In contrast, the method of forming grooves on the sheet surface, in which the magnetic domain refinement effect is not lost even if annealing is performed, is called heat resistant magnetic domain refinement. Wound core type transformers need stress relief annealing in the manufacturing process, and stacked core type transformers do not require stress relief annealing. For the reason mentioned above, non-heat resistant magnetic domain refinement can be used in stacked core transformers.

## 2.3 History of Iron Loss Improvement at JFE Steel

### 2.3.1 Development of “JGH™”

The history of improvement of the iron loss of grain-oriented electrical steel at JFE Steel is shown in Fig. 4. The development of grain oriented electrical steel at JFE Steel began in 1948 at a predecessor company of JFE Steel, Kawasaki Heavy Industries. Manufacture and sales of grain oriented electrical steel sheets (“RG”; current trade name: “JG”) began in 1959, and sales of the product trade-named “RGH™” (current trade name: “JGH™”) began in 1973.

In grain-oriented electrical steel, the metallurgical phenomenon called secondary recrystallization is used to the alignment of the crystal orientation. Secondary recrystallization is a phenomenon in which only grains with a near-Goss orientation among primary grains with a size of around 10 μm grow to 5 mm or larger. In particular, in order to align the <001> direction, which is the direction of easy magnetization, with the rolling direction, it is essential to use an inhibitor, which inhibits the growth of grains with orientations other than the Goss orientation. As inhibitors in “RGH™,” in addition to fine precipitates, the inhibiting force is strengthened by using segregation elements. As a result, hysteresis loss is reduced, and it is possible to reduce iron loss by approximately 10% from the level in conventional grain oriented electrical steel sheets.

Since the alignment of the crystal orientation was improved and a certain level of hysteresis loss reduction was achieved, the primary focus of subsequent research shifted to reduction of eddy current loss. After the commercialization of “RGH” in 1973, Oil Crises occurred successively in 1973 and 1979. With the sharp rise in energy prices and the heightened opportunities for energy conservation worldwide due to these Oil Crises, “RGH” also achieved further evolution. As techniques for reducing eddy current loss, reducing the thickness of the steel sheet, increasing the Si content and refinement of the grain size were studied. During secondary recrystallization, inhibitors tend to decompose and be lost from the steel sheet surface layer. However, that ten-

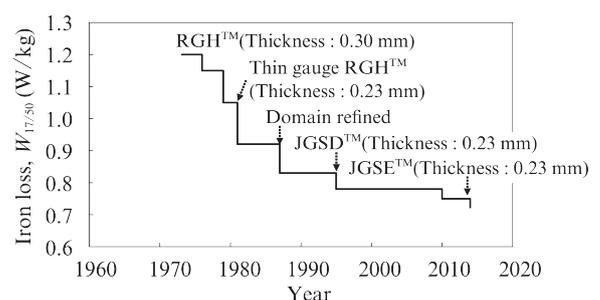


Fig. 4 Historical trend of iron loss improvement in JFE Steel

dency is intensified in thinner sheets, and as a result, secondary recrystallization becomes unstable or the alignment of the crystal orientation deteriorates. For this reason, only thick materials with thicknesses of 0.27 mm or more were commercialized until the beginning of the 1980s. Moreover, increasing the Si content also tends to destabilize secondary recrystallization. Although development was extremely difficult, a new metallurgical technology was incorporated in the manufacturing process, and sales of the thin-gauge grain oriented electrical steel sheet “23RGH” with a thickness of 0.23 mm began in 1981. Following this, research on even thinner gauges was carried out, and JFE Steel began sales of the grain oriented electrical steel sheet “20RGH” with a thickness of 0.20 mm in 1983. Since an iron loss evaluation system had been introduced in the United States at that time, these thin-gauge grain oriented electrical steel sheets were adopted by many transformer manufacturers and earned an excellent evaluation.

### 2.3.2 Development of Magnetic Domain-Refined Materials

Unlike the metallurgical methods for improving iron loss described above, a method for reducing excess eddy current loss by reducing the magnetic domain width by a physical technique, in which the magnetic domains are refined by introducing local strain in the surface of the grain-oriented electrical steel sheet, was developed. Various methods for introducing strain were studied, for example, marking by scratches or hard balls, laser irradiation, and so on<sup>3-6)</sup>. In 1987, JFE Steel succeeded in commercializing a magnetic domain-refined material by a plasma jet irradiation method<sup>7)</sup> and marketed this material under the trade name Plasma Core “RGHPJ.” If a gas is heated to high temperature, violent impact between the gas particles occurs, resulting in separation into electrons and positive ions. This mixed state of electrons and ions is called plasma. As a technique applied to magnetic domain refinement, a gas is plasma-tized by an arc discharge, forcibly converged by a nozzle orifice and high speed gas flow, and jetted from the nozzle. In the plasma jet irradiation method, magnetic domain refinement was performed by irradiating a plasma jet with a temperature of 10 000°C or higher, which was obtained in this manner, on a grain oriented electrical steel sheet. However, magnetic domain refinement methods using local strain by laser irradiation, plasma jet irradiation and the like could not be used with wound core type transformers, in which stress relief annealing (approx. 800°C) is necessary, because the iron loss improvement effect is lost if the product is heated to 500°C or higher.

Therefore, JFE Steel (at the time, Kawasaki Steel) promoted development of heat resistant magnetic

domain-refined materials which are capable of withstanding stress relief annealing, and succeeded in 1991 in obtaining a magnetic domain refinement effect by forming grooves on the surface of the steel sheet and utilizing the diamagnetic field effect of the magnetic poles formed on the groove side faces<sup>8,9)</sup>. This heat resistant magnetic domain-refined material was marketed under the trade name “RGHPD.” As it also has the advantage of applicability to both stacked cores and wound cores, “RGHPJ” was later unified with “RGHPD.”

### 2.3.3 Development of “JGS™”

Following this progress in reducing eddy current loss by introducing magnetic domain refinement technologies, JFE Steel once again targeted enhancement of the alignment of the crystal orientation and reduction of hysteresis loss. The company reviewed the entire manufacturing process of “RGH™” from the metallurgical viewpoint, and in 1994, developed “New RGH” (“RGH-N”; current trade name: “JGS™”) and “New RGHPD” (“RGHPD-N”; current trade name: “JGSD”), which is produced by heat resistant magnetic domain-refining treatment of “New RGH.” The crystal orientation of primary recrystallized grains has a large influence on the crystal orientation of secondary recrystallization grains. Therefore, JFE Steel introduced Japan’s first electron back scattering diffraction (EBSD) device to evaluate the orientation of primary recrystallized grains, and clarified the proper orientation of primary recrystallized grains which should be targeted by constructing a new texture evaluation model<sup>10)</sup>. This resulted in further progress in the properties of “New RGH.”

### 2.3.4 Further Improvement of Iron Loss

JFE Steel promoted iron loss improvement in “JGSD™” and marketed a heat resistant magnetic domain-refined material “23JGSD080” with a sheet thickness of 0.23 mm and  $W_{17/50} \leq 0.80$  W/kg.

The company also developed a new non-heat resistant type magnetic domain refinement technique which is different from the previous plasma jet method, and began sales of the “JGSE™” series in 2014. The highest grade material in the “JGSE™” series is “23JGSE075,” which is a non-heat resistant magnetic domain-refined material with a sheet thickness of 0.23 mm and  $W_{17/50} \leq 0.75$  W/kg. This product has won an excellent evaluation for use in stacked core type transformers.

### 3. Product Lines and Transformer Characteristics

#### 3.1 Line-up of Grain Oriented Electrical Steel Sheet Products

JFE Steel's current line-up of grain oriented electrical steels is shown in Fig. 5. From low grade materials, grain-oriented electrical steels are generally classified as 3 types, namely, CGO, HGO, and magnetic domain-refined materials. However, in order to respond to diverse customer needs, JFE Steel classifies grain oriented electrical steels in 5 series, "JG," "JGH™," "JGS™," "JGSD™," and "JGSE™."

The "JG" series consists of general grain oriented electrical steel sheets with thicknesses of 0.27 mm to 0.35 mm and corresponds to the above-mentioned CGO.

The "JGH™" series comprises high grade materials with thicknesses of 0.20 mm to 0.35 mm and is equivalent to HGO. This series has superior iron loss in comparison with the "JG" series.

The "JGS™" series is a higher grade series with thicknesses of 0.23 mm to 0.35 mm; this series is equivalent to HGO and offers a combination of high magnetic flux density and low iron loss characteristics. Due to its high accumulation of the grain orientation to the Goss orientation, it is also extremely effective in realizing low noise in transformers.

The "JGSD™" series comprises heat resistant type magnetic domain-refined materials in which grooves are formed on the steel sheet surface, and is a low iron loss grain-oriented electrical steel which can also be used in wound core type transformers produced by stress relief annealing.

The "JGSE™" series comprises non-heat resistant magnetic domain-refined materials in which local strain is introduced in the steel sheet. These products are low

iron loss grain oriented electrical steels with excellent iron loss characteristics for use in stacked core type transformers.

It should be noted that only representative products are shown in Fig. 5. Designations such as "35JG135" indicate the sheet thickness, grade and guaranteed value of iron loss ( $W_{17/50}$ ). For example, in the case of "35JG135," this designation shows sheet thickness: 0.35 mm, grade: JG and guaranteed value of iron loss: 1.35 W/kg.

#### 3.2 Transformer Characteristics with "JGSE™"

The following shows an example in which "23JGSE075," which is currently the highest grade non-heat resistant magnetic domain-refined material, and "23JGSD080," which is a heat resistant magnetic domain-refined material, are applied in a stacked core type oil-filled transformer. The rated capacity of the transformer is 1 000 kVA, and the core is a three-phase, three-leg stacked core type. Table 1 shows the magnetic properties of the materials used, and Fig. 6 shows the relationship between the excitation magnetic flux density and iron loss. "23JGSE075" and "23JGSD080" both show superior transformer iron loss characteristics in comparison with those predicted in case "JG" and "JGH™" are used. Furthermore, in comparison with "23JGSD080," "23JGSE075" displays low iron loss over the entire excitation flux density range, thus showing the most favorable iron loss characteristics in stacked core type transformers.

Table 1 Magnetic properties of sheets for transformers

Sheets grade	Magnetic flux density, $B_8$ (T)	Iron loss, $W_{17/50}$ (W/kg)
23JGSD080	1.902	0.742
23JGSE075	1.936	0.713

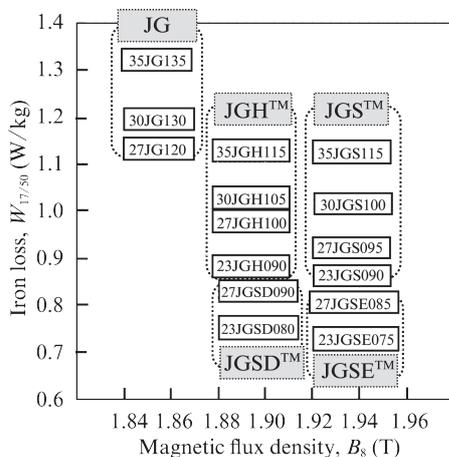


Fig. 5 Product line-up of grain oriented electrical steels of JFE Steel

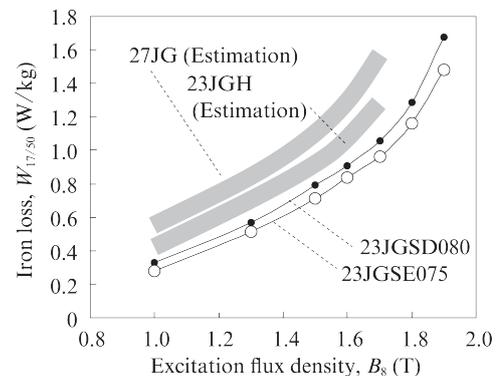


Fig. 6 No-load losses of stacked core transformers of highest grade domain refined grain oriented electrical steels

### 3.3 Future Outlook

In the field of grain-oriented electrical steel, JFE Steel has responded to the needs of customers by developing the world's highest level of products in heat resistant magnetic domain-refined materials, non-heat resistant magnetic domain-refined materials and others. However, there are also increasingly strong demands for global energy conservation and global warming countermeasures. To address these needs, JFE Steel carried out research and development on next-generation grain oriented electrical steel under commission from Japan's New Energy and Industrial Technology Development Organization (NEDO)<sup>11)</sup>.

In that research and development project, unlike the conventional grain oriented electrical steel sheets, a TiN film was formed on the steel base metal by using chemical vapor deposition (CVD) technology. The TiN film makes it possible to apply large tension to the steel sheet. As a result, when experimental coils were manufactured on a pilot line, a 16% iron loss reduction was successfully realized in the developed material, and an excellent iron loss value of  $W_{17/50} = 0.63$  W/kg could be obtained in comparison with the iron loss value of  $W_{17/50} = 0.75$  W/kg of 23JGSD080, which was the base material. Moreover, in a 30 kVA wound coil type transformer using the developed material, improvements of 11–12% in no-load loss (iron loss) at rated voltage ( $B_m = 1.7$  T) and 21–23% at 110% of rated voltage ( $B_m = 1.91$  T) were achieved in comparison with the conventional material.

As future technical development, we plan to supply even more outstanding grain-oriented electrical steels by promoting improvement of magnetic domain-refining technologies, improvement of the alignment of crystal orientation, increased electrical resistance of steel sheets, development of thinner gauge products, etc.

### 4. Conclusion

Since JFE Steel began the manufacture and sale of grain oriented electrical steels in 1959, the company has consistently pursued technologies for realizing low iron loss. JFE Steel now supplies the following as its highest grade products.

- (1) Heat resistant type magnetic domain-refined grain-oriented electrical steel capable of withstanding stress relief annealing, "23JGSD080" ( $W_{17/50} \leq 0.80$  W/kg)
- (2) Non-heat resistant type magnetic domain-refined material suitable for stacked core type transformers, "23JGSE075" ( $W_{17/50} \leq 0.75$  W/kg)

In order to contribute to worldwide energy conservation and global warming countermeasures through high efficiency in transformers, in the future, JFE Steel will continue to work to further reduce iron loss in grain oriented electrical steel.

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