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Recent Progress of High Silicon Electrical Steel in JFE Steel†

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Abstract:

JFE Steel has developed high silicon steel sheets in response to the demand for improved high switching frequency characteristics. Since starting commercial production of 6.5% Si steel sheet (Super Core^{TM}) in 1993, JFE Steel has developed several new products (Gradient silicon steel sheet: "JNHF^{TM}"and"JNSF^{TM}") for high freqency applications. This paper introduces the overview and application of representative JFE Steel's Super Core products.

1. Introduction

Applications of electrical equipment in the market have increased in recent years, as exemplified by use of renewable energy and growth of hybrid vehicles powered by electrical energy. Because high efficiency and compact size are demanded in the electrical equipment used in these applications, the performance necessary to realize higher efficiency and downsizing is also required in their component materials. Moreover, as high efficiency and downsizing of electrical equipment have led to moves to high in operating frequencies, improvement of high frequency magnetic characteristics is also demanded in their iron core materials.

This paper introduces the basic material properties, centering on magnetic characteristics, of the high silicon electrical steel sheets of the Super Core^{TM} series possessed by JFE Steel as magnetic materials responding to high frequency requirements, and also describes improvement of formability, which is considered necessary for expanding the market for high Si materials, and presents examples of application when Super Core is used in motor applications, where adoption of high frequency materials is progressing.

2. High Si Electrical Steel Sheets Super Core^{TM}: "JNEX^{TM}," "JNHF^{TM}," and "JNSF^{TM}"

2.1 6.5% Si Steel Sheet "JNEX^{TM}"

When the Si content in steel sheets is increased, the electrical resistance of the sheets increases, eddy current loss is reduced, and high-frequency iron loss is improved. At around a Si content of 6.5 wt%, it is known that magnetic permeability is maximized and the magnetostriction constant becomes substantially zero. In order to reduce eddy-current loss, a sheet thickness on a level that requires cold rolling is necessary, but because it is not possible to keep mechanical properties capable of withstanding cold rolling if the Si content is increased, industrial production of high Si steel sheets had not been realized. To overcome this problem, JFE Steel carried out development of a production technology utilizing chemical vapor deposition (CVD) from the second half of the 1980s, and began the world's first industrial production of high Si electrical steel sheets in 1993 [1]. **Figure 1** shows an outline of production by the CVD process. Concretely, after rolling low Si steel, which can be cold-rolled, to obtain the required thin-gauge thickness, heating is performed in a non-oxidizing atmosphere, and $SiCl_4$ gas is blown to the both back and front sides of the steel sheet under that high temperature environment. This causes a substitution reaction between

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"Super Core" is registered trademark of JFE Steel Corporation in Japan.

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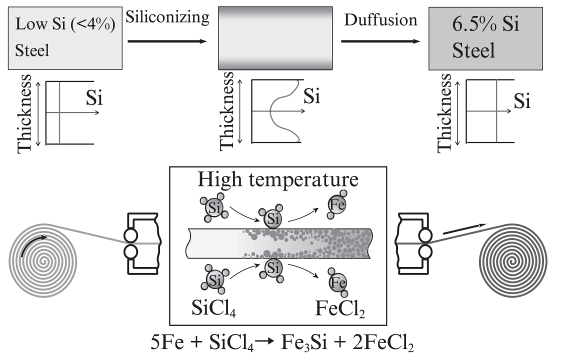

Fig. 1 Manufacturing process of 6.5% Si steel

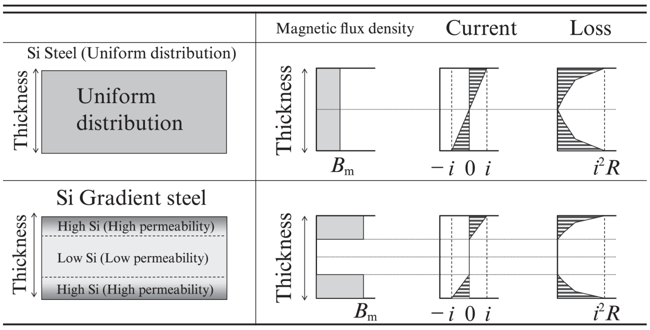

Fig. 2 Image of Si gradient steel performance

the Fe and Si in the surface layer of the steel sheet, and Si is added continuously to the sheet. After this, soaking treatment is then performed at high temperature. This makes it possible to manufacture of the uniform high Si sheet JNEX™ in a continuous process.

2.2 Gradient High Si Steel Sheet "JNHF™"

In materials treated by continuous CVD siliconizing, JFE Steel discovered a phenomenon in which materials with a gradient Si concentration in the sheet thickness direction display superior high-frequency iron loss, and began industrial production of the gradient magnetic material "JNHF™." [1] In this gradient magnetic material, it was possible to reduce eddy-current loss by controlling the Si concentration distribution in the sheet thickness direction so as to obtain a high magnetic permeability layer in the surface layer. This decrease of eddy-current loss can be arranged by a schematic concept as shown in **Fig. 2**. Due to the difference in magnetic permeability caused by the change in the Si concentration of the surface and inner layers, magnetic flux concentrates in the surface layer in the excited state. Assuming that the magnetic flux concentrates in that surface layer part, and there is no change in the magnetic flux further to the inside from the surface layer, an eddy current, which is caused by changes in magnetic flux density, will also be generated only in the surface layer. Therefore, eddy-current loss is reduced in comparison with the case in which the magnetic flux passes through the sheet uniformly in the sheet thickness direction. Particularly in the frequency range of 10 kHz and higher, "JNHF" has superior iron loss characteristics in comparison with the uniform 6.5% Si steel sheet "JNEX™," and is contributing to improvement of efficiency in high frequency reactors.

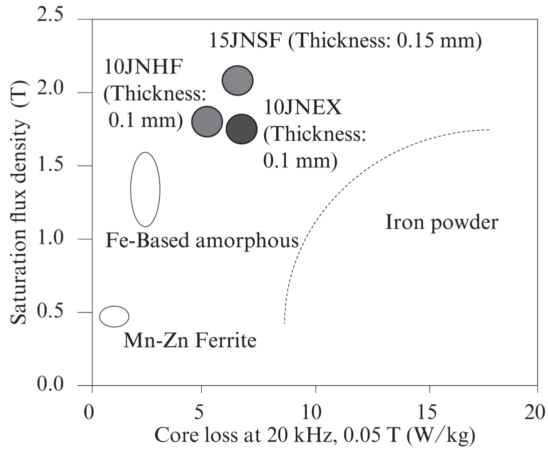

Fig. 3 Overview of magnetic property at high frequency

2.3 High B_s Gradient Si Steel Sheet "JNSF™"

As a material which makes the maximum use of the effect of gradient magnetic materials in reducing eddy-current loss in the high frequency region, JFE Steel developed "JNSF™," which further expands the Si concentration gradient in the sheet thickness direction in comparison with the conventional "JNHF™." [2] In "JNSF," the Si concentration gradient in the sheet thickness direction is increased by controlling the phase structure of the steel sheet during CVD siliconizing and utilizing the difference in the Si diffusion rates of the respective phases. As a result, a larger eddy-current loss reduction effect has been obtained.

In comparison with the conventional gradient magnetic material "JNHF," "JNSF" also shows higher saturation magnetic flux density characteristics due to its lower average Si concentration. **Figure 3** shows a comparison of the magnetic properties of various high frequency core materials. "JNSF," which is a gradient magnetic material that makes the maximum use of the strong points of continuous siliconizing, is positioned as a material that satisfies both reduction of high-frequency iron loss, contributing to higher efficiency in electrical equipment, and high magnetic flux density, realizing downsizing of electrical equipment. Considering these advantages, expanded application is expected.

Table 1 Typical magnetic properties

Material	Thickness (mm)	Saturation magnetic flux density (T)	Core loss (W/kg)				Magnetostriction at 400 Hz, 1.0 T ($\times 10^{-6}$)
			400 Hz	5 kHz	10 kHz	20 kHz	
			1.0 T	0.2 T	0.1 T	0.05 T	
10JNEX900	0.10	1.8	5.7	11.3	8.3	6.9	0.1
10JNHF600	0.10	1.9	10.1	11.2	7.1	5.4	3.1
15JNSF950	0.15	2.0	15.0	14.9	9.7	7.0	2.8
Grain oriented Si steel	0.10	2.0	6.4	20.0	18.0	14.0	−0.8
Fe-based amorphous	0.025	1.5	1.5	8.1	3.6	3.3	27.0

2.4 Basic Properties of "JNEX™," "JNHF™," and "JNSF™" Materials

Table 1 shows the typical magnetic properties of Super Core™ products. The table also shows examples of the properties of ultra-thin grain oriented Si steel and Fe-based amorphous as representative high frequency materials. Amorphous shows good iron loss properties in all frequency regions due to the effect of its thin sheet thickness, but its magnetostriction constant is large, and its saturation magnetic flux density is also on the lower side in comparison with electrical steel sheets. Thus, in high frequency reactor applications, size and noise are drawbacks. Ultra-thin grain oriented electrical steel sheets have high saturation magnetic flux density, but high-frequency iron loss is large; when used as core materials for high frequency reactors, electrical steel sheets are disadvantageous from the viewpoints of efficiency and heat generation. Super Core has an excellent balance of saturation magnetic flux density and high-frequency iron loss, and when used in high frequency reactors, there appears to be effective in realizing the optimum design in terms of efficiency and physical constitution. Moreover, the magnetostriction constant of "JNEX™" is small in comparison with the other materials, and this can contribute to low noise in reactors.

In processing as reactor core materials, the core winding is considered to be the normal processing method for amorphous due to its thin sheet thickness. However, also based on cases in which multiple gaps were introduced, this processing method requires additional equipment investment due to the increased number of processes such as core cutting, etching, etc., and for this reason, mass productivity and cost are issues. Since the basic processing method with Super Core is the laminated core using bonding in the mold, the manufacturing process comprises only a press-forming process. Also considering the low initial investment and freedom in the design core dimensions, it is possible to satisfy both mass productivity and cost reduction.

Figure 4 shows the core loss properties of Super Core standard products. Comparing materials having the sheet thickness of 0.1 mm, 10JNHF600, which is a gradient magnetic material, shows superior iron loss properties in the high frequency range above the frequency of 5 kHz in comparison with 10JNEX900, which has a uniform Si concentration in the sheet thickness direction. The high saturation magnetic flux density (B_s) gradient magnetic material 15JNSF950 shows superior iron loss properties in the frequency range of frequencies of 20 kHz and higher in comparison with the uniform Si material 10JNEX900, in spite of the larger sheet thickness of 15JNSF950. This is due to the effect of the Si concentration distribution in the sheet thickness direction. This feature also enables cost reduction, for example, by reducing the cost of sheet cutting by using a thicker sheet thickness, etc., without sacrificing high-frequency iron loss performance. In high frequency reactors, which are the main application of the Super Core series, 10JNEX900, which is the uniform Si material with low magnetostriction properties, is frequently used when noise is a priority, while 10JNHF600 is used when efficiency is prioritized. In the future, expanded needs for 15JNSF950 are considered likely, also supposing cases in which importance is attached to cost.

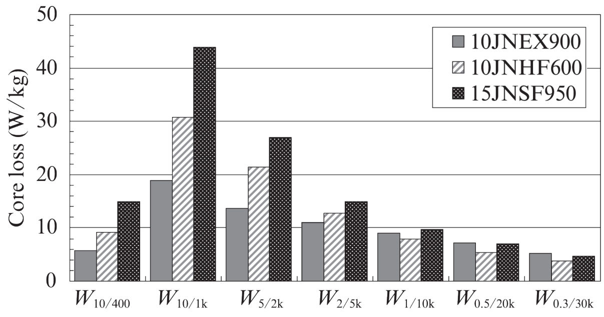

Fig. 4 Core losses of "JNEX™," "JNHF™," and "JFSF™"

3. Improvement of Formability of Super Core™

3.1 Need for Improved Formability

In expanding the market for Super Core™, which offers excellent high frequency magnetic characteristics, the formability of the material was an issue from the start of production. In many cases, steel strips manufactured by continuous CVD siliconizing are slit and then press-formed (shearing, punching) to the core shape, and in some cases, winding is performed after slitting. Material formability which can withstand this type of processing is necessary. Moreover, accompanying the expansion of applications in recent years, punching in complex shapes has also be required.

3.2 Improvement of Formability

From the beginning of development, cracks frequently occurred in the elastic region stage in room temperature plastic working of Super Core^{TM}, and measures were also considered necessary in winding, for example, by increasing the winding inner diameter, etc. However, JFE Steel also discovered cases in which Super Core products manufactured by the same process could amply withstand room temperature forming. Therefore, this material with satisfactory formability was investigated[3].

Photo 1 shows the appearance of the cracked parts in materials with different formability. In the material with good formability, the crack can be observed in the grains, whereas in the hard-to-form material, the crack occurred at the grain boundary. Based on this difference in the crack morphology, it is considered that the properties of the grain boundary influence formability.

Therefore, the elements that exist at the grain boundaries of the materials which were the objects of study were investigated. In this investigation, the sample materials were cooled to the temperature of liquid nitrogen, impact was applied in a vacuum chamber to cause intergranular (grain boundary) fracture, and the fracture surfaces were investigated by Auger analysis. **Figure 5** shows the measurement results. As a strong peak of oxygen was observed at the grain boundary of the hard-to-form material, a difference in comparison with the good formability material was confirmed. In high temperature annealing, it is known that the surface and grain boundaries of steel sheets oxidize due to moisture and trace amounts of oxygen in the atmosphere gas, and it was thought that the grain boundaries also oxidized in the same manner in Super Core.

In order to clarify the relationship between grain boundary oxidation and formability, samples with different grain boundary oxidation conditions were prepared by performing heat treatment at 1 200°C with different furnace atmosphere dew points. The object materials was 6.5 wt% Si steel sheets (Thickness: 0.3 mm) prepared with a warm rolling mill in the laboratory. As an evaluation of formability, the stroke length to fracture in the 3-point bending test was measured, and the oxygen concentration at the grain boundary of the evaluated samples was then measured by Auger analysis. **Figure 6** shows the results of this evaluation of the relationship between stroke length and the grain boundary oxygen concentration.

As the grain boundary oxygen concentration increases, it can be understood that the stroke length to fracture becomes shorter, indicating deterioration of formability. Based on these investigation results, measures to prevent oxidation in the furnace were implemented by equipment improvement and material design, and improvement of the formability of products after CVD siliconizing was realized.

As a result of formability improvement, it became possible to perform room temperature punching of complex shapes, such as motor shapes, which had been con-

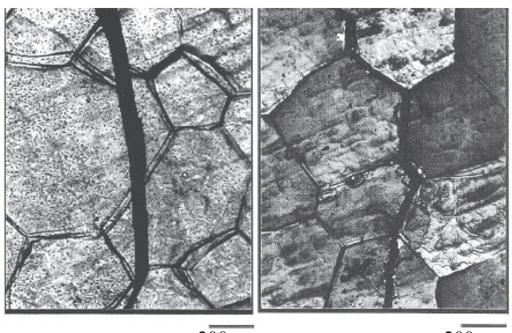

Photo 1 Appearance of the crack

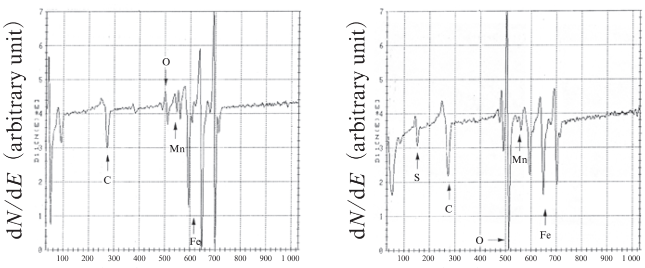

Fig. 5 Analysis of grain boundary

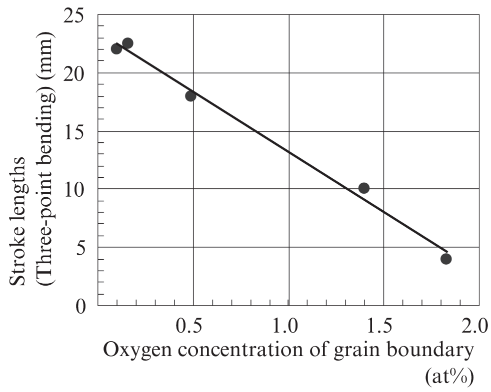

Fig. 6 Result of three-point bending test

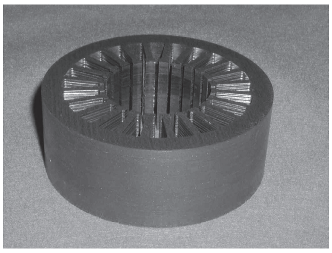

Photo 2 Example of punching product (10JNEX900)

sidered impossible by room temperature processing with the conventional material. **Photo 2** shows an example of a motor core punching product. The material used here is JFE's 6.5% Si steel sheet 10JNEX900. Punching was performed at room temperature, and laminate fixing was done by bonding.

JFE Steel is also engaged in technical collaboration with customers in connection with core processing and is responding to a diverse range of processing needs.

Recently, JFE Steel has also responded to a large number of evaluations of next-generation motors and has realized motor core processing for diverse shapes and supplied those results to the market.

4. Examples of Application of Super Core™

4.1 Needs for Motor Core Materials

Higher efficiency and downsizing of motor equipment has shown remarkable progress from the viewpoint of effective utilization of energy. Adoption of high operating frequencies by higher motor speeds is progressing gradually, and low iron loss at high frequency is demanded in motor core materials. Because Super Core™ has excellent low iron loss at high frequency, application to motor cores is expected. JFE Steel carried out an evaluation of the effectiveness of material property improvement by using a proprietary motor evaluation system.

4.2 Examples of Application of Super Core™ to Motors

JFE Steel carried out an evaluation of the effectiveness of core materials for motor efficiency by using the motor evaluation system shown in **Photo 3** [4)].

Figure 7 shows the results of measurements of motor efficiency when Super Core™ is used as the core material. **Table 2** shows the magnetic properties of Super Core and non-oriented electrical steel sheets which were evaluated as comparison materials. As measurement conditions, motor efficiency was measured at different motor speeds at a maximum output of 2 kW using a 4-pole interior permanent magnet (IPM) type motor with core dimensions of a stator outer diameter of φ105 mm and a stack thickness of 45 mm. The motor efficiency of Super Core exceeded that of the high grade general electrical steel sheets from the low motor speed region to the high speed region. In particular, in the high speed range of 5 000 rpm and higher, an excellent result, namely an efficiency improvement on the order of 2%, was obtained.

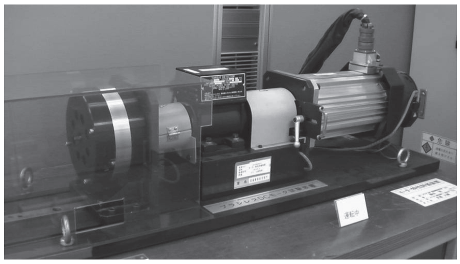

Photo 3 Model motor evaluation system

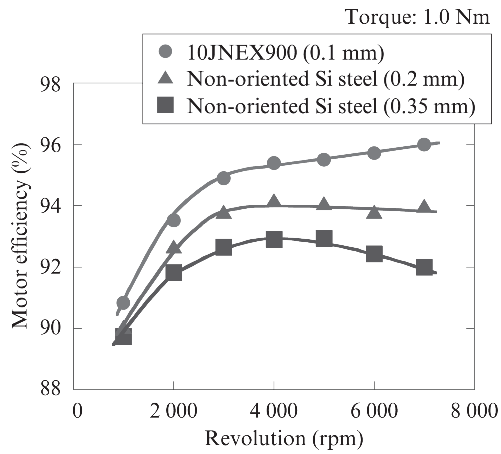

Fig. 7 Motor efficiency and motor speed [4)]

Table 2 Magnetic properties of motor test material

Material	Thickness (mm)	Core loss (W/kg) 50 Hz 1.0 T	400 Hz 1.0 T	1 kHz 1.0 T	10 kHz 0.1 T	Permeability direct current	Magnetostriction at 400 Hz, 1.0 T ($\times 10^{-6}$)
10JNEX900	0.1	0.5	5.7	18.7	8.3	23 000	0.1
Non-oriented Si steel	0.2	0.9	10.9	39.7	20.2	10 500	3.5
	0.35	0.9	16.6	71.1	36.6	10 300	3.0

Table 2 shows an outline of the magnetic properties of the materials used in the evaluation. The effect of the material in reducing iron loss in the high frequency region shows a similar tendency to the results of improvement of motor efficiency in the high speed region. Higher efficiency than that of conventional non-oriented electrical steel sheets can be expected by using Super Core as a core material for the higher motor speeds of the future.

5. Conclusion

JFE Steel developed Super Core™, which has excellent high frequency magnetic properties for realizing high efficiency and downsizing, in response to the trend toward high frequency in electrical equipment, and was the first in the world to achieve industrial production of this type of high Si electrical steel. Room temperature forming of high Si steel sheets, which had been considered difficult with conventional materials, was achieved by suppressing grain boundary oxidation, and technology for realizing processing of diverse motor core shapes was established, making it possible to supply cores that respond to market needs. JFE Steel also developed "JNSF™," which makes maximum use of the effect of a Si concentration gradient in the sheet thickness direction, by phase structure control during CVD siliconizing treatment, thereby realizing a material which satisfies both the ideal high saturation magnetic flux density and low iron loss at high frequency in a high frequency magnetic material. In the future, Super Core is also expected to contribute to the field of power electronics, where further progress in the use of high frequencies is expected as a result of technical innovation in semiconductor devices, etc. In the future, JFE Steel will continue to develop materials that respond to the need for high frequency characteristics.

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