JFE TECHNICAL REPORT
No. 6 (Oct. 2005)

High Silicon Steel Sheets Realizing Excellent High Frequency Reactor Performance†

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Abstract:

JFE Steel has developed two types of high silicon steel sheets suitable for high frequency applications, JFE Super Core "JNEX-Core" and "JNHF-Core." In this paper, the magnetic properties of JNEX and JNHF are compared with those of thin-gauge grain-oriented electrical steel sheets and iron-based amorphous, which are representative high frequency materials. High frequency reactors were manufactured using each of these materials, and their reactor performance was examined. As results, it was found that JNHF can realize low loss performance in high frequency reactors, as it shows little deterioration in core loss as a result of the core manufacturing process, and can also improve the DC bias characteristics of high frequency reactors, while JNEX makes it possible to realize a large reduction in audible noise in high frequency reactors due to its excellent magnetostriction characteristic.

1. Introduction

Social concern regarding the global environment is increasing by the year. For this reason, there has been renewed interest in reducing energy consumption in recent years, including its potential contribution to reducing emissions of environmental load substances. In other words, the problem of energy saving and related technologies have again become matters of great concern, as can be seen, for example, in heightened interest in the hybrid car.

This paper examines the magnetic properties of JFE Steel's high silicon electrical steel sheets (Super Core series) as outstanding materials for high frequency reactors, which are important components for realizing energy saving in power equipment, and describes reactor performance when these materials were used in the reactor cores.

2. Inverter/Converter Technology and High Frequency Reactors

Inverter/converter technology has become a key technology for energy saving in the field of power electronics[1)]. With this technology, power conversion and control are performed with high efficiency and high speed/high accuracy utilizing the switching action of semiconductor power devices.

In realizing inverter/converter technology, high frequency reactor are critical electronic components which are as indispensable as the semiconductor elements. The high frequency reactor is the part responsible for the function of voltage/current regulation in the circuit, which it performs by cyclically charging/discharging electric energy in the circuit accompanying switching operation. In view of the fact that downsizing of parts, including high frequency reactors, and improved equipment controllability can be achieved by increasing the switching speed, development efforts have been consistently oriented toward realizing higher switching frequencies.

The switching frequency of inverter/converter devices is generally dependent on the capacity of the device. Therefore, in large-capacity devices with capacities of several hundreds kiro volt ampere or more, switching frequencies of several hundreds to several kiro hertz are generally adopted, while in medium-capacity devices

† Originally published in *JFE GIHO* No. 8 (June. 2005), p. 11–16


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(several hundreds volt ampere to several hundreds kiro volt ampere), switching frequencies are on the order of several kiro hertz to several tens kiro hertz, and in small-capacity devices (less than several hundreds volt ampere), the switching frequencies are several tens kiro hertz to several hundreds kiro hertz.

The high frequency reactors used in inverter/converter devices can be broadly divided into DC reactors and AC reactors.

For example, in order to cut higher order harmonic components, including the switching frequency, in the inverter output stage, an LC filter is normally installed. In this circuit configuration, the L component (inductance component) is carried by the high frequency reactor. Because the waveform of the current passing through this reactor takes a form in which a high frequency ripple is superposed over a low frequency alternating current, as shown in **Fig. 1**, this type of reactor is particularly termed an AC reactor.

Furthermore, for example, voltage conversion is frequently performed internally in inverter/converter devices. In the majority of cases, this is achieved using a chopper-type DC-DC converter circuit, and an inductance component using a high frequency reactor is also essential in this circuit configuration. In this case, the current waveform passing through the reactor takes a form in which a high frequency ripple is superposed over a DC current, as also illustrated in Fig. 1. Accordingly, this type of reactor is particularly termed a DC reactor.

In addition to the above, high frequency reactors have also become essential parts in inverter/converter devices used for other purposes, including examples such as power factor correction circuits (active filters)[2], secondary side filters for switching transformers, and others which are installed to solve the problem of higher harmonics in power sources while simultaneously improving efficiency.

In both AC reactors and DC reactors, the current waveform includes the higher order harmonic component caused by switching. For this reason, excellent high frequency magnetic properties are necessary in iron core materials for use in high frequency reactors. In particular, there had been a strong need for the development of new soft magnetic materials possessing a combination of low core loss at high frequencies for realizing low reactor loss, high saturation flux density for reactor downsizing, and low magnetostriction for reduction of audible noise in the reactor.

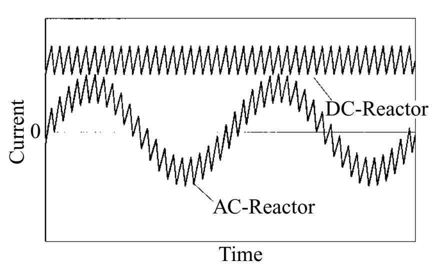

Fig. 1 Reactor current wave

As outstanding materials which meet the above-mentioned requirements of iron core materials for high frequency reactors, JFE Steel developed the world's first line of high Si electrical steel sheets under the tradename JFE Super Core.

3. High Si Electrical Steel Sheets JFE Super Core "JNEX-Core" and "JNHF-Core"

3.1 6.5% Si Steel Sheet, JNEX-Core

Silicon is added to electrical steel sheets in order to increase their resistivity. In particular, because the eddy current loss in iron cores rises rapidly as the frequency increases, Si addition is extremely effective in improving the high frequency magnetic properties of electrical steel sheets. It is also known that the magnetostriction of steel sheets is changed by adding Si to Fe, and reaches zero at an Si content of 6.5 mass%[3].

Thus, high Si electrical steel sheets, and particularly 6.5% Si steel sheets, display extremely good high frequency magnetic properties. However, the ductility of steel sheets decreases as the Si content increases, and the material shows remarkable embrittlement when the Si content exceeds 3.5 mass%, making cold rolling difficult. For this reason, production of high Si electrical steel sheet with added Si contents exceeding 3.5 mass% at the industrial level had been difficult.

To solve this technical problem, JFE Steel established the world's first continuous production technology for 6.5% Si steel sheets using chemical vapor deposition (CVD)[4]. **Figure 2** shows the principle of the manufacturing process for 6.5% Si steel sheets by CVD. First, a low Si steel thin sheet which is manufactured easily by cold rolling is selected as the base material. This is heated to a high temperature in a non-oxidiing atmosphere. When $SiCl_4$ is supplied to the high temperature sheet surface, the Fe in the steel sheet and the Si in the $SiCl_4$ gas undergo mutually substitution, and Si penetrates into the steel sheet. An Si-enriched layer is formed in the surface layer of the sheet by this chemical reaction. The Si is then diffused to the interior of the steel sheet by high temperature soaking in an non-oxidizing atmosphere, finally resulting in a steel sheet with a uniform 6.5% Si content.

This material is marketed under the trade-name JNEX-Core.

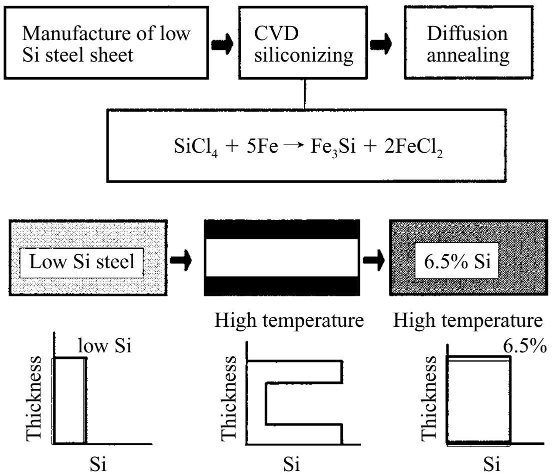

Fig. 2 Manufacturing process of 6.5% Si steel

3.2 Magnetic Gradient High Si Steel Sheet, JNHF-Core

Gradient function materials, which are characterized by a continuous change in composition in the thickness direction, have been developed mainly in the fields of heat-resistant and thermoelectrical materials. The authors discovered that electrical steel sheets having an Si content distribution (gradient) in the sheet thickness direction display unique magnetic properties, and carried out research and development focusing on this fact. As a result, a magnetic gradient high Si steel sheet with new magnetic properties, which could not be realized in conventional electrical steel sheets, was successfully developed by controlling the concentration distribution pattern in the sheet thickness direction. In particular, in the high frequency region, the new sheet possesses a low core loss property exceeding that of 6.5% Si steel sheets.

As in the production of 6.5% Si steel sheets, this new magnetic gradient high Si steel sheet is produced by a process of siliconizing by CVD, followed by diffusion treatment using the continuous siliconizing line. In the production of magnetic gradient high Si steel sheets, the product with the desired Si concentration distribution is obtained by controlling the amount of siliconzing during formation of the Si-enriched layer in the sheet surface layer and the siliconizing rate, and then controlling the temperature and treatment time during high temperature soaking in the non-oxidizing atmosphere. As shown in **Fig. 3**, the magnetic gradient high Si steel sheets obtained by this process have a concentration distribution pattern in which the Si concentration increases continuously from the sheet center to the surface layer, and have a 6.5 mass% Si composition in the sheet surface layer with extremely high magnetic permeability.

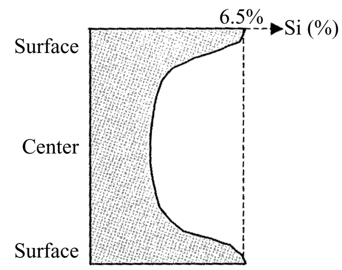

Fig. 3 JNHF Si profile

This material is marketed under the trade-name JNHF-Core[5)].

3.3 Magnetic Properties of JNEX-Core and JNHF-Core

Table 1 shows examples of the typical magnetic properties of JNEX and JNHF. The table also shows examples of the typical magnetic properties of thin-gauge grain-oriented silicon steel sheet (thin-gauge GO) and Fe-based amorphous, which are representative materials for high frequency applications.

Fe-based amorphous shows low core loss over the entire frequency region because the sheet thickness is extremely thin and its resistivity is high. However, because its saturation magnetization is low and magnetostriction is large, it has been pointed out that this material has problems related to downsizing and audible noise in reactor applications.

On the other hand, thin-gauge GO has high saturation magnetization, but it has also been pointed out that this material has problems of heat generation and low efficiency in reactors due to its large core loss.

In comparison with these materials, JNEX and JNHF both possess an excellent balance of the properties of core loss and saturation magnetization considering application in high frequency reactors. Comparing JNEX and JNHF at a sheet thickness of 0.1 mm, as shown in

Table 1 Typical magnetic properties

Material	Thickness (mm)	Specific resistance ($\mu\Omega \cdot m$)	Saturation magnetization (T)	Core loss (W/kg)				Magnetostriction at 400 Hz, 1.0 T ($\times 10^{-6}$)
				50 Hz, 1.0 T	400 Hz, 1.0 T	5 kHz, 0.2 T	20 kHz, 0.05 T	
10JNEX900	0.1	0.82	1.8	0.5	5.7	11.3	6.9	0.1
10JNHF600	0.1	–	1.9	1.1	10.1	11.2	5.0	–
Grain oriented Si steel	0.1	0.48	2.0	0.7	6.4	20.0	14.0	−0.8
Fe base amorphous	0.025	1.30	1.5	0.1	1.5	8.1	3.3	27.0

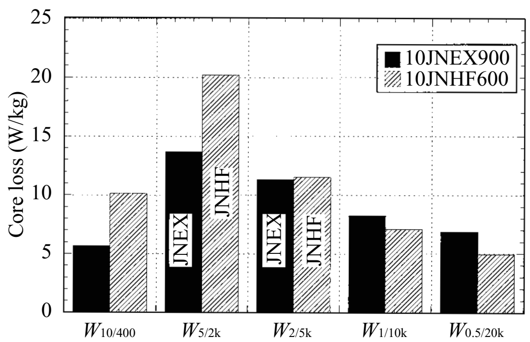

Fig. 4 Core losses of JNEX and JNHF

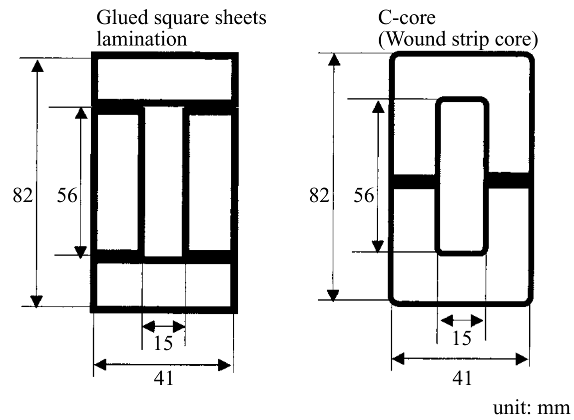

Fig. 5 Dimensions of iron cores

Fig. 4, JNEX displays excellent core loss characteristics at frequencies below a borderline value of 5 kHz, while JNHF exhibits excellent core loss performance at higher frequencies than this.

Therefore, in current high frequency reactor applications, JNEX is mainly used when the switching frequency is several kiro hertz or less, and JNHF is used at frequencies of 10 kHz and higher. Recently, however, the number of examples where low audible noise is required in high frequency reactors has increased rapidly, and cases where JNEX is used under such conditions now make up the majority.

4. Performance of High Frequency Reactors Using JNHF-Core

4.1 Material Suitable for Low Core Loss in Reactors, JNHF-Core

In comparison with 6.5% Si steel sheets, which had possessed the highest magnetic properties among conventional Fe-Si alloys, JNHF displays low core loss in the high frequency region exceeding 5 kHz. It is therefore an excellent material for high frequency reactor cores with switching frequencies of 10 kHz or higher, where reactor loss has become a major problem.

4.2 Experimental Procedure

The structures of high frequency reactor cores can be broadly divided into stacked cores and strip wound cores. In cases where thin-gauge GO is used, the strip wound type is optimal because the direction of magnetization is limited to the direction with high magnetic properties (i.e., the rolling direction). Likewise, the strip wound core is also the optimal choice when amorphous is used, considering the high processing costs and the difficulty of gap control, due to the extremely thin sheet thickness (0.025 mm) used in stacked cores.

On the other hand, with JNHF, the punched block-type stacked core is normally used because the material itself is non-oriented and deterioration of magnetic properties due to heat treatment in the strip wound core manufacturing process is a concern.

Therefore, in the present research, cores of identical dimensions were manufactured, as shown in **Fig. 5**, using a block-type core (stacked core built up from glued square sheets) with JNHF, and C-type cores (wound strip core) with thin-gauge GO and Fe-based amorphous, so that a comparative evaluation of the high frequency reactor performance of the materials could be carried out using the most suitable core structure for the respective materials.

In general, it is necessary to provide an air gap in the magnetic path in reactor cores in order to prevent magnetic saturation. The authors discovered that the size of this air gap influences the core loss characteristics of reactor cores. The air gap length dependency of core loss was therefore investigated using a frequency of 20 kHz and flux density of 0.05 T.

Moreover, because DC bias characteristics are extremely important in the performance of high frequency reactors, being as important as core loss characteristics, the DC bias current dependency of the inductance value at a frequency of 20 kHz and flux density of 0.01 T was also investigated.

4.3 Experimental Results

Table 2 shows the core loss of the base materials used in core manufacturing, the core loss when the air gap in the manufactured core was zero, and the core loss increase(%) attributable to the core manufacturing process. In the case of thin-gauge GO and Fe-based amorphous, the cores were of the strip wound type and stress relief annealing was performed as part of the manufacturing process, but in both cases, the core loss characteristics showed deterioration. The rate of this deterioration (increase in core loss) was particularly large with the Fe-based amorphous. In contrast, with JNHF, no deterioration in core loss was observed. Thus, this experiment confirmed that substantially the same core loss characteristics as in the base material can be obtained in manufactured cores using JNHF.

Table 2 Core loss increase by core manufacturing

Material	Thickness (mm)	$W_{0.5/20k}$ (W/kg) Raw material	Manufac-tured core	Core loss increase by core manufacturing (%)
10JNHF600	0.1	4.89	4.88	0
Grain oriented Si steel	0.1	9.75	10.24	5
Amorphous	0.025	1.31	2.20	68

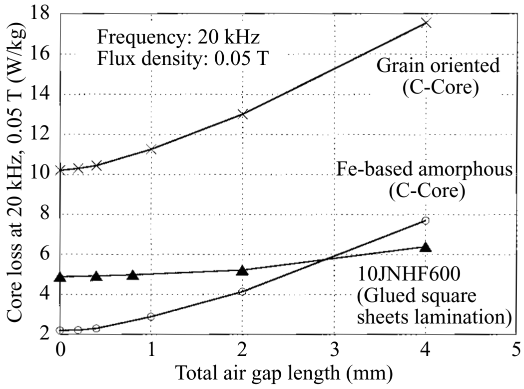

Fig. 6 Core loss dependence on gap length

Figure 6 shows the air gap length dependency of core loss at a frequency of 20 kHz and flux density of 0.05 T. With the thin-gauge GO and Fe-based amorphous, core loss increases rapidly as the total air gap length increases, but in contrast, with JNHF, the rate of increase in core loss as the total air gap length increases is markedly smaller than with the other two materials.

This is attributed to the gap dispersion effect. Specifically, because leakage flux in the vicinity of the gap increases rapidly as the gap length increases, core loss due to this leakage flux also increases greatly. However, because the number of air gaps is large in cores made from JNHF, as can be understood from Fig. 5, the gap length of each air gap is smaller when compared at the same total gap length. As a result, it is thought that leakage flux is also smaller, reducing the increment of core loss.

Thus, the fact that it is possible to use a punched-and-stacked core structure, in which a large number of gaps can be formed because JNHF is a non-oriented material with low strain sensitivity, is another outstanding feature of this material.

Figure 7 shows the DC bias current dependency of the inductance value at a frequency of 20 kHz and flux density of 0.01 T.

In comparison with the other materials, it was found that JNHF displays greatly superior inductance performance in the high current region of DC bias current. This performance is an extremely useful feature for power reactors. As to the reason why JNHF displays this high DC bias characteristic, because the DC magnetic

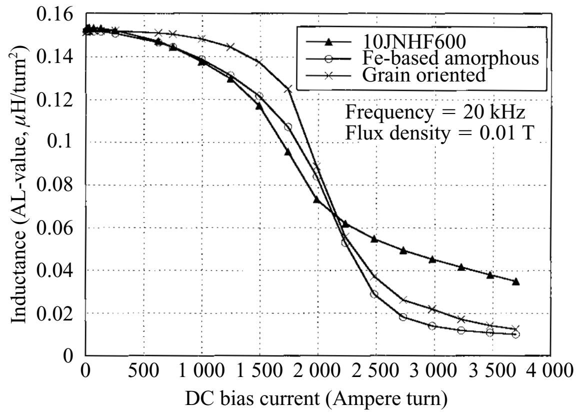

Fig. 7 Inductance dependence on DC bias current

Table 3 Magnetic permeability of raw materials

Material	Magnetic permeability (emu) DC (μmax)	20 kHz, 0.05 T
10JNHF600	4 100	1 500
Grain oriented Si steel	37 000	1 110
Amorphous	300 000	5 450

permeability of JNHF is low, as shown in **Table 3**, it resists magnetic saturation by the DC bias current, while on the other hand, because its high frequency magnetic permeability is high, a sufficiently high value of high frequency inductance can be secured. In other words, JNHF is a material with an extremely good balance of DC magnetic permeability and high frequency magnetic permeability as a core material for high frequency reactors.

5. Performance of High Frequency Reactor Using JNEX-Core

5.1 Material Suitable for Low Noise in Reactors, JNEX-Core

Magnetostriction is the cause of audible noise in high frequency reactors. Because the 6.5% Si steel sheet JNEX has the extremely good feature of zero magnetostriction, which is not found in other electrical steel sheets, it is the optimal core material for low noise reactors.

5.2 Experimental Procedure

Cut cores of the same dimensions as the strip wound core (C-core) shown in Fig. 5 were manufactured using each of the materials JNEX (thickness: 0.1 mm) and thin-gauge GO and Fe-based amorphous (thickness: 0.025 mm). Test reactors were manufactured by inserting a gap material (thickness: 0.2 mm) in each of the cores at two points, fixing the cores with a stainless band, and wrapping the cores with a coil (22 turns). The reactors were then excited using a PWM wave with a fundamental frequency of 50 Hz and a carrier frequency of 16 kHz, and the audible noise (A scale) of the reactors was measured at a position 10 cm from the core.

5.3 Experimental Results and Discussion

Figure 8 shows the flux density (peak value) dependency of core loss under PWM excitation. The frequency analysis on the core loss shows that the loss component at a fundamental frequency (50 Hz) is lower in thin-gauge GO than in JNEX. However, under PWM excitation, JNEX shows lower core loss. This is because PWM includes a large number of higher order harmonic components, and the core loss associated with these higher harmonics is markedly lower in JNEX than in thin-gauge GO[6, 7].

Figure 9 shows the flux density dependency of audible noise under PWM excitation. JNEX showed an extremely low value of audible noise in the high frequency reactor, reflecting the magnetostriction characteristics of the base material. Moreover, the results also showed that the difference in noise between JNEX and the other materials increased as the flux density became higher.

As described above, use of JNEX in reactor cores makes it possible to reduce high frequency loss while also holding audible noise to an extremely low value. It can therefore be said that JNEX is the optimal material for achieving low audible noise in high frequency reactors.

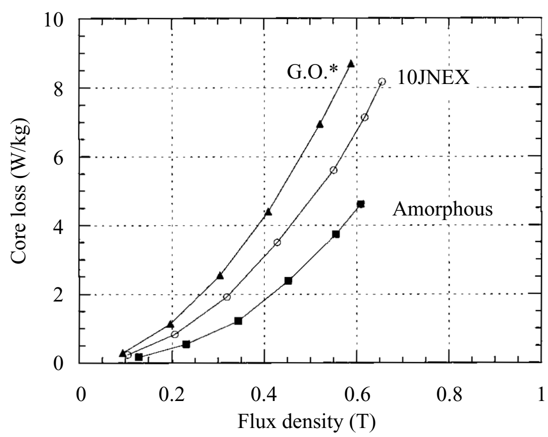

Fig. 8 Core losses of test reactors

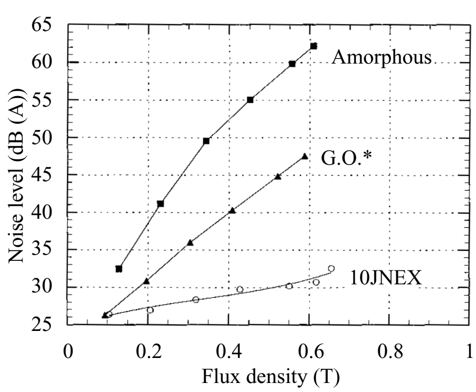

Fig. 9 Audible noise of test reactors

6. Conclusion

High frequency reactors were manufactured using JFE Steel's high frequency electrical steel sheets, JNEX-Core and JNHF-Core, and thin-gauge grain-oriented silicon steel sheets and Fe-based amorphous, which are representative materials for high frequency applications. The magnetic properties of the materials were evaluated using these test reactors, revealing the following:

(1) JNHF-Core has an excellent balance of DC magnetic permeability and high frequency magnetic permeability, and therefore displays extremely good loss characteristics and DC bias characteristics in high frequency reactors.

(2) JNEX-Core possesses an excellent magnetostriction property, making it possible to realize a large reduction in audible noise in high frequency reactors.

JFE Steel's Super Core products possess excellent magnetic performance as materials for high frequency reactors, as described in this report. These products are widely used in switching power supply devices for power applications, and recently have also been increasingly adopted in power supply components for hybrid cars. These outstanding materials are playing significant roles in environmental protection and energy saving.

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