Soft Magnetic Materials of JFE Steel Group†

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Abstract:

Iron-based soft magnetic materials are widely used as cores, such as transformers, motors, and generators. The soft magnetic materials developed by the JFE Steel Group include grain oriented electrical steels, non-oriented electrical steels, Super Core (6.5%Si-Fe), soft ferrites, and iron powder. The applications of these soft magnetic materials cover a wide range of frequencies, from commercial frequency to approximately 1 MHz. In addition to improving the properties of individual materials, the JFE Steel Group also investigates the optimum methods of applying these diverse materials through the evaluation of transformers and motors.

1. Introduction

Ferromagnetic materials are classified as hard magnetic materials, such as permanent magnets, which externally supply magnetic flux semi-permanently once being magnetized, and soft magnetic materials, such as those used in electromagnet cores, which cease to supply flux when the electric current passing through the coil is stopped. This paper will discuss the latter type, soft magnetic materials.

Iron-based soft magnetic materials are used in the cores of electrical equipments such as transformers, generators, and motors. Reducing losses generated from materials of these applications contributes directly to improving energy conversion efficiency. From the viewpoint of energy saving and environmental awareness in recent years, improvement of soft magnetic materials is an important issue for society as a whole.

The followings are examples of representative soft magnetic materials of the JFE Steel Group.

(1) Electrical Steels

These are sheet-type materials which are produced by adding around 3% silicon to high purity iron. Iron loss under alternating magnetic fields is reduced to the absolute minimum by applying advanced metallurgical treatments. The thickness of grain oriented electrical steels is mainly in the range of 0.23–0.35 mm, while that of non-oriented products is 0.20–0.65 mm. With both types, a thin insulation coating is painted and baked on the sheet surface to reduce the eddy currents generated under alternating magnetic fields.

Electrical steels are used in the stacked cores of transformers and motors, which are rarely seen by the ordinary people. However, world production of electrical steels exceeds 5 million tons/year. To begin with, electrical power is produced by large generators with electrical steel cores. In distributing the generated power to homes and factories, the voltage is stepped up or down by transformers which also use electrical steel cores. The end user applications of electrical power use cover a diverse range such as lighting, heating, and mechanical power applications. In particular, mechanical power is produced by various kinds of motors. Together with improving convenience in everyday life, the applications of motors are also extremely diverse, including air-conditioners, washing machines, vacuum cleaners, refrigerators, and information technology equipment. Thus, electrical steels are used in all of the processes of power generation, transmission, distribution, and use. However, because electrical steels are essentially a metallic material with electrical conductivity, the application frequency range is at most 100 kHz from the direct current range, even when their thickness

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is reduced to 0.10 mm, as in the case of JFE Steel's Super Core.

(2) Soft Ferrite

The soft ferrites developed, produced, and sold by the JFE Steel Group include MnZn-type and NiZn-type soft ferrite material powders and MnZn soft ferrite cores. Because the base material resistivity of MnZn soft ferrite is higher than metallic materials such as electrical steel, by 10^6–10^{10}, soft ferrite can be used at higher frequencies from 100 kHz to 1 MHz. Conversely, their saturation flux density is on the order of 0.5 T, which is only about 1/4 that of electrical steel. However, because soft ferrite can cover a high frequency range, of an order 1 000 times higher than electrical steels, in the field of compact switching power sources, they are widely used with switching devices such as MOS-FET and IGBT which are now under remarkable performance improvement.

(3) Iron Powder

Unlike electrical steels, which are manufactured in sheet form, iron powder cores enable a further reduction in eddy currents by cutting off eddy current paths in 3 dimensions. JFE Steel's iron powder is a pure iron-type reduced iron powder with a size on order of 100 μm. Accordingly, the increased resistivity of iron powder cores is realized not by elements which increase resistivity, such as silicon, but rather, by adding insulation resin, which is mixed with the powder during compacting, between the particles. This type of iron powder core is widely used in choke cores for switching power sources and in noise filters, commonly used under the frequency range from 10 kHz to 100 kHz.

The following describes the features of these respective materials in greater detail.

2. Soft Magnetic Materials of JFE Steel

2.1 Electrical Steels

2.1.1 Grain oriented electrical steels[1)]

Grain oriented electrical steels are extremely high performance materials in which the <001> orientation, which is the direction of the axis of easy magnetization of iron, is aligned with the rolling direction in the product coil. Crystals of this material consist of single crystals with a size of millimeter order, as shown in **Photo 1**, and thus differ completely from the polycrystals in ordinary steel sheets, which are somewhat more than 10 μm in size. Furthermore, deviation of the axis of easy magnetization from the rolling direction is controlled to within 8°. This product, in which the crystals in an extremely long steel band reaching as much as several thousands meters are oriented uniformly within a range of several degrees, truly deserves to be called a "work of art" in steel.

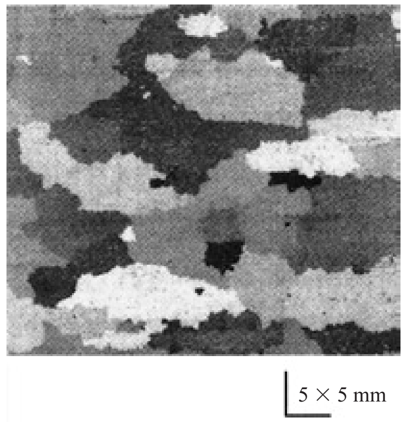


Photo 1 Typical macrostructure of grain oriented electrical steel

The product properties of grain oriented electrical steels are commonly discussed in terms of the magnetic flux density B_8 (magnetic flux density at magnetizing force of 800 A/m), which is a characteristic related to the alignment of the crystallographic orientation, and iron loss (for example, $W_{17/50}$: loss per unit of weight at a magnetic flux density amplitude of 1.7 T at 50 Hz). The B_8 and $W_{17/50}$ of current representative products of the JFE Steel Group are shown in **Table 1**. JFE Steel manufactures products with B_8 of 1.85–1.93 T and $W_{17/50}$

Table 1 Typical magnetic properties for JFE G-core

Type	Symbol	Thickness (mm)	$W_{17/50}$ (Wkg)	B_8 (T)
JG	35JG135	0.35	1.33	1.85
JGH	30JGH105	0.30	1.03	1.89
JGH	23JGH090	0.23	0.88	1.89
JGS	30JGS105	0.30	0.99	1.93
JGS	23JGS090	0.23	0.87	1.92
JGSD	23JGSD085	0.23	0.78	1.88

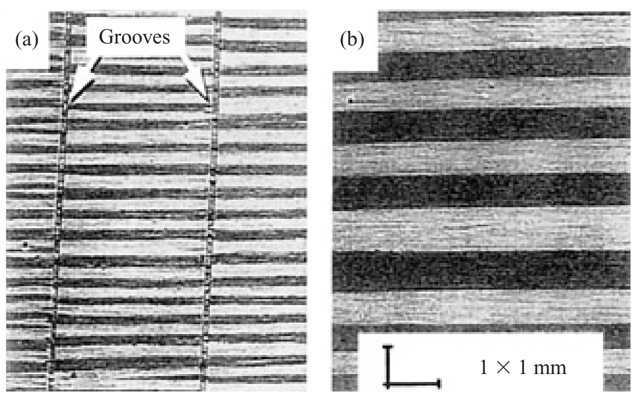


Photo 2 Magnetic domain structure of (a) grooved and (b) plain materials observed by type-II Lorentz SEM method

of 0.78–1.33 W/kg (all figures are representative values). The values of magnetic flux density B_8 increase in the order of JG, JGH, and JGS, reaching high magnetic flux densities of 1.89 T in JGH and 1.93 T in JGS. Stable production of these grain oriented electrical steels with high magnetic flux densities exceeding 1.88 T is achieved using a combination of advanced metallurgical technologies, including secondary recrystallization. Iron loss is reduced by enhancing the crystallographic orientation and reducing the material thickness. Widely used products are 23JGH and 23JGS (thickness: 0.23 mm). 23JGSD is a product with extremely low loss, which is produced by forming the fine linear grooves shown in **Photo 2** to 23JGS. In 23JGSD085, $W_{17/50}$ is reduced to 0.78 W/kg.

High performance grain oriented electrical steels mainly contribute to higher efficiency in transformers in two respects, that is, by realizing low iron loss and by reducing the exciting current. High magnetic flux density materials also contribute to more compact size by making it possible to increase the design flux density of the transformer, and to reduced transformer noise by low magnetostriction characteristics.

2.1.2 Non-oriented electrical steels[2)]

Non-oriented electrical steels, unlike the grain oriented electrical steels discussed above, consist of polycrystals with sizes of around 100 μm and are designed so as to minimize magnetic anisotropy in the steel sheet plane. Like grain oriented steels, the properties of non-oriented electrical steels are also characterized in terms of magnetic flux density B_{50} (magnetic flux density at magnetizing force of 5 000 A/m) and iron loss (for example, $W_{15/50}$: loss at magnetic flux density amplitude of 1.5 T at 50 Hz).

The main non-oriented electrical steel products manufactured by JFE Steel are shown in **Fig. 1**[3)].

JN Core conforms to the JIS Standard and is available in thicknesses of 0.35 mm and 0.50 mm. This line-up includes products with iron loss $W_{15/50}$ ranging from 7.2 W/kg with 50JN1000, which is a low-Si product, to 1.98 W/kg with high-Si 35JN200.

In these JIS Standard materials, magnetic flux density decreases as iron loss is reduced. JNE Core is a new product which possesses a higher magnetic flux density at the same iron loss, displaying a 0.03–0.05 T higher value of B_{50} in comparison with JN Core. Furthermore, when performance is compared at the same iron loss, JNE Core also has the advantage of reduced hardness. In designing the material to achieve these property improvements, JFE conducted an exhaustive study of the effect of the resistivity-increasing elements Si, Mn, and Al on electrical resistivity and hardness, and applied a technology for reducing the (111) texture, which is detrimental to magnetic properties, by adding grain boundary segregation elements and optimizing the intermediate processes. These property improvements not only increase the efficiency of electrical equipments such as motors, but also have the merit of reduced die wear due to the lower hardness of the material.

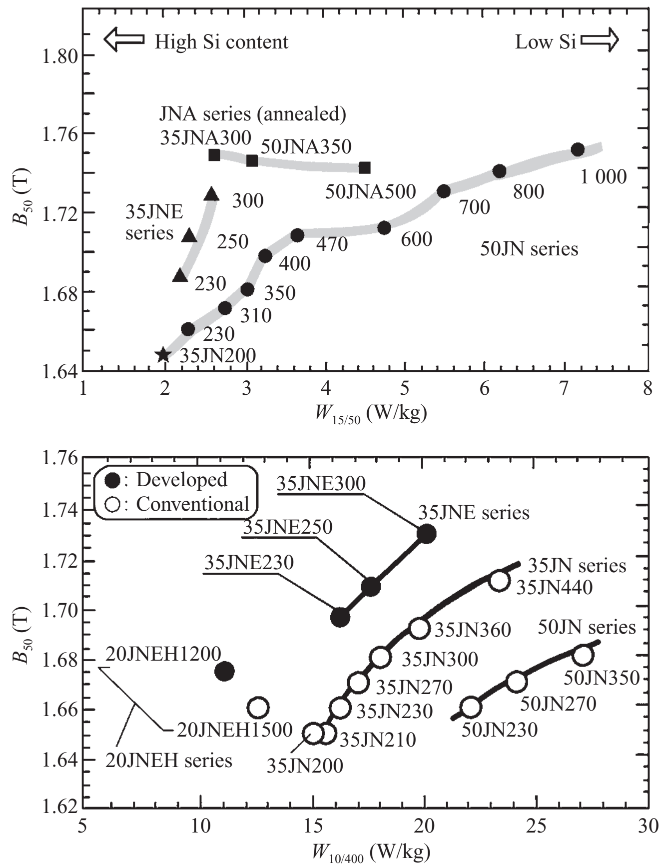


Fig. 1 Maps of non-oriented electrical steel products of JFE Steel

JNEH Core is a 0.20 mm thick material which was developed to meet recent needs for higher frequency operation. Its properties are standardized using $W_{10/400}$ rather than the conventional $W_{15/50}$. For example, the $W_{10/400}$ of 20JNEH1200 is 11 W/kg. In comparison with 35JN230 (16.2 W/kg) and 50JN250 (24 W/kg), the value for 20JNEH is equivalent to a reduction in iron loss of 32% and 54%, respectively. This clearly shows the effectiveness of reducing the sheet thickness in the high frequency range, since the difference in these materials is not remarkable when compared at $W_{15/50}$.

In recent years, needs related to motors, which are the main application of non-oriented electrical steels, have greatly changed in terms of motor type, control technology, and applications. The mainstream motor type has shifted from induction motors to permanent magnet motors, while inverter control has largely replaced commercial power source control. Moreover, high rotational speed devices such as hard disk motors and motors for hybrid vehicles are increasing. In all these applications,

Table 2 Typical magnetic properties for Super core

Thickness (mm)	Symbol	$W_{10/1\,k}$ (Wkg)	$W_{1/10\,k}$ (Wkg)	$W_{0.5/20\,k}$ (Wkg)	Magnetostriction ($\times 10^{-6}$)
0.10	10JNEX	18.7	8.3	6.9	$<$0.1
0.20	20JNEH	42.0	21.0	–	8.0
0.23	23JGSD	35.0	26.5	–	1.0

there is a tendency of requiring improved high frequency iron loss characteristics in core materials, because the higher frequencies in core excitation and superposition of higher harmonics are inevitable. The 20JNEH Series was developed to respond to these needs in high speed motors.

2.1.3 Super Core (6.5% Si steel)

Super Core is a steel sheet containing 6.5% Si. As noted previously, Si is a resistivity-increasing element. Although increased addition of Si is effective in reducing eddy current, the electrical steels described above are manufactured by rolling and annealing, and when Si addition exceeds 3.5%, the material generally becomes brittle, making a rolling process difficult[4]. On the other hand, it has long been known that 6.5% Si addition is extremely effective for improving permeability and reducing magnetostriction[4]. JFE Steel therefore developed a continuous siliconization process using CVD (chemical vapor deposition) to overcome this difficulty in manufacturing sheets with higher Si contents[5]. In this revolutionary method, thin sheets are first manufactured using 3% Si steel, and then Si is diffused in the sheet by CVD in order to achieve a higher Si content. JFE Steel is currently the world's only commercial manufacturer of 6.5% Si steel.

The lineup of Super Core products is shown in **Table 2**. Sheet thicknesses range from 50 μm to 100 μm. Together with the high resistivity of Super Core, these products can be used more effectively than conventional electrical steels in the high frequency range of 400 Hz–100 kHz.

The properties of Super Core are evaluated mainly in terms of iron loss ($W_{1/10K}$: iron loss at flux density of 0.1 T and frequency of 10 kHz, and $W_{0.5/20K}$). With 100 μm Super Core, $W_{1/10K}$ is 8.3 W/kg. In comparison with 0.20 mm non-oriented electrical steel (21 W/kg) and 0.23 mm grain oriented electrical steel (26.5 W/kg), a large reduction in iron loss is possible with Super Core.

Super Core is frequently used as reactors in circuits operated by MOS-FET and IGBT high speed switching devices. The saturation flux density of Super Core products, as shown in **Fig. 2**, is slightly low in comparison with the 2.0 T of conventional electrical steels, but is more than 3 times higher than the 0.5 T of soft ferrite cores. Because this makes it possible to realize a compact sectional area in the core, Super Core is extremely effective for downsizing electrical devices.

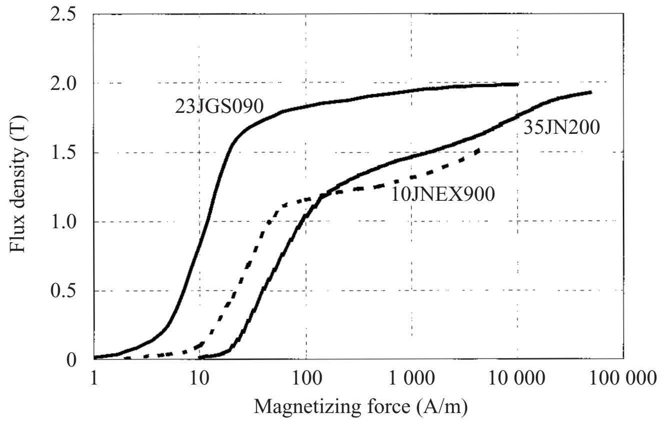


Fig. 2 Typical magnetization curve for JFE G-core, N-core, and Super core

As another important advantage, Super Core has a zero magnetostriction in principle. Because magnetostriction is one of the main causes of acoustic noise, this value, which is 1/10 that of grain oriented electrical steel and less than 1/80 that of non-oriented electrical steel, enables a remarkable reduction in noise.

As described above, Super Core products are high saturation flux density metallic-type soft magnetic materials which cover the intermediate frequency range between the electrical steels and soft ferrite, and are also ideal low noise materials.

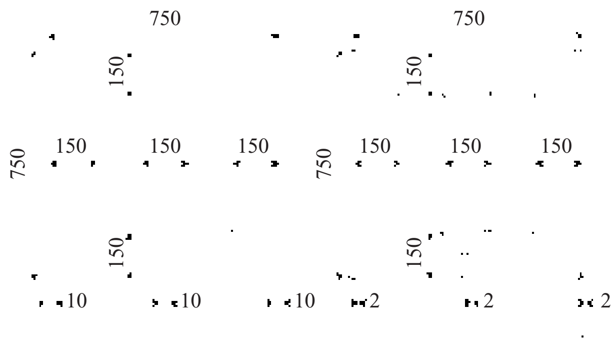
2.1.4 Development of application technologies for electrical steels

In addition to the development of the electrical steels, as described above, JFE Steel also evaluates the effectiveness of material properties improvements using the motor evaluation system[3] and transformer evaluation system[6,7] shown in **Photo 3**.

An example of an evaluation of the relationship between the magnetic flux density B_8 of the material and the noise level in transformers is shown in **Fig. 3**. This figure clearly demonstrates the point that increasing material magnetic flux density by reducing dispersion of the crystallographic orientation in grain oriented electrical steels can contribute to reduced noise levels in transformers.

As shown in **Fig. 4**, an evaluation of brushless DC motors revealed that iron loss at frequencies higher than the fundamental frequency of 100 Hz (e.g., $W_{10/400}$) gov-

(a) Model motor evaluation system



(a) Alternate-lap joint (b) Step-lap joint

unit : mm

(b) 3-phase transformer evaluation system

Photo 3 Model motor and transformer evaluation systems

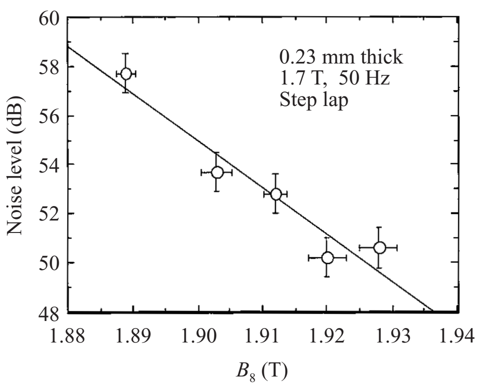


Fig. 3 Relationship between material flux density and transformer noise level

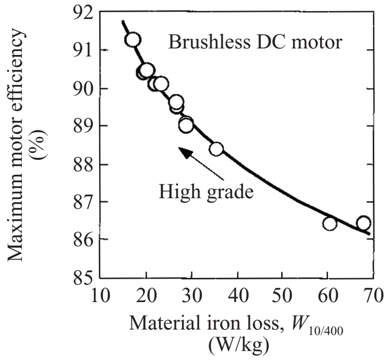


Fig. 4 Relationship between material iron loss $W_{10/400}$ and maximum motor efficiency

erns motor properties. Based on this knowledge, JFE Steel has developed materials which reduce iron loss in the high frequency region, as described above.

2.2 Soft Ferrite

The soft ferrite cores produced and sold by the JFE Steel Group are MnZn soft ferrite. These products are widely used as cores in switching power supplies, mainly at frequencies of several tens of kHz and higher. MnZn soft ferrite cores are sintered compacts with a ternary oxide system consisting of Fe_2O_3, MnO, and ZnO. Because the JFE Steel Group produces high purity iron oxide for soft ferrite, the group has advantages in both raw material development and stable supply. The JFE Steel Group also succeeded in developing the world's first roller hearth kiln with advanced atmospheric control, and using this, established a high efficiency, high productivity manufacturing technology as well as high material performance. Employing this advanced sintering technology, JFE Steel Group has achieved a homogeneous crystal structure and high resistivity in MnZn soft ferrite, and has succeeded in sintering ultra-large cores like that shown in **Photo 4**.

The world's leading low loss materials, MB3 and MB4, were developed using this quality control technology. Responding to changing customer needs in addition to these low loss materials, the JFE Steel Group has developed unique materials such as MBT2, which shows low loss from room temperature to around 120°C making it the optimum product for onboard use in automobiles, MBF4, which can be used with a wide range of frequencies, and other soft ferrite products[8)].

Loss in MnZn soft ferrites is generally evaluated by the loss value at 200 mT and 100 kHz, as shown in **Fig. 5**. With the aforementioned MB4, loss at 100°C is 300 kW/m^3 or less, and with MBT2, the variation in loss over the temperature range of 20–120°C is controlled to 280–360 kW/m^3. MBF4 is a low loss material for high frequency use, displaying loss of no more than 300 kW/m^3 at both 200 mT/100 kHz and 100 mT/300 kHz.

These soft ferrite cores are used in the power sup-

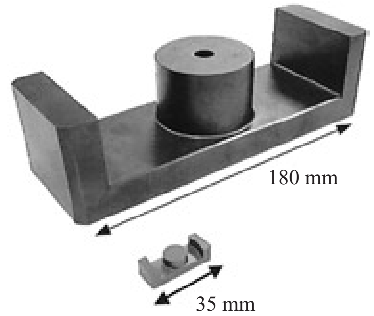


Photo 4 Example of large size soft ferrite core

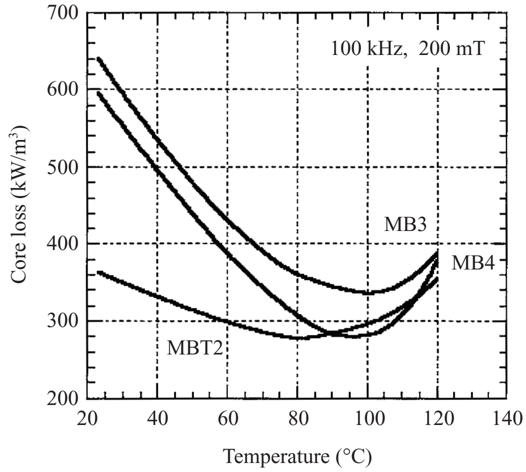


Fig. 5 Temperature dependence of core loss at 100 kHz and 200 mT of low loss materials, MB3,MB4, and MBT2

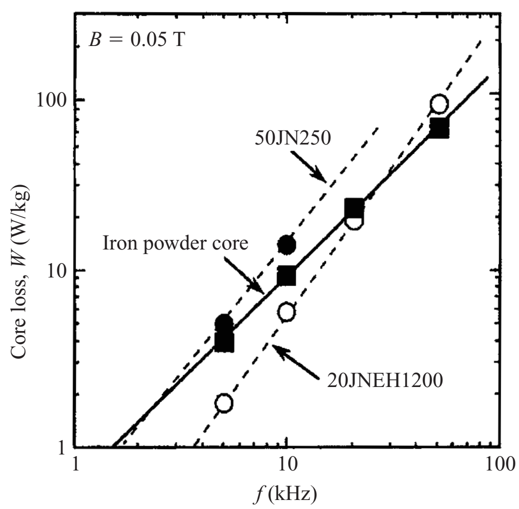


Fig. 7 Comparison of core loss for iron powder core with non-oriented electrical steels

ply circuits of various home electrical appliances, such as switching power supplies for personal computers. In the future, low loss soft ferrite cores described above, are expected to contribute to improved efficiency, particularly in DC-DC converter circuits for stepping down from the main battery voltage to the voltage required in auxiliary devices in hybrid cars.

2.3 Iron Powder

As an iron powder with improved magnetic properties, JFE Steel produces and sells the reduced iron powder JIP MG270H. To improve the magnetic properties of iron powder, JFE conducted a detailed analysis of the effect of the impurity content, particle size, and residual strain in the iron powder on initial permeability[9], and as shown in **Fig. 6**, developed a material which displays high initial permeability (≧74) in comparison with conventional cores manufactured under identical compacting conditions.

The results of a comparison of the core loss characteristics of ring-shaped compacted powder cores made from this material and cores made from non-oriented electrical steels 50JN250 and 20JNEH1200 are shown

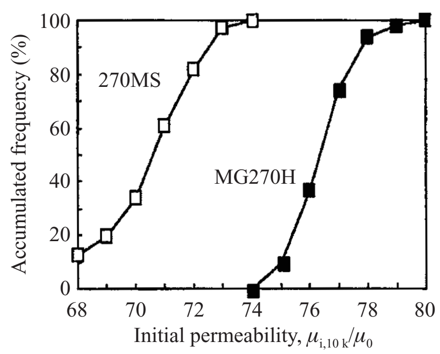


Fig. 6 Accumulated frequency of initial permeability of iron powder cores

in **Fig. 7**. Loss in the powder cores is superior to that of 50JN in the frequency region of 2 kHz and higher, and is superior to that of 20JNEH in the region over 20 kHz. Thus, compacted iron powder cores have properties which complement conventional electrical steels and soft ferrite cores with improved performance in the intermediate frequency range.

If it is possible to satisfy the requirements of both improvement in loss up to high frequencies and additional improvement in initial permeability and saturation flux density by increasing the density of the green compact, a further expansion of the range of applications can be expected in the future, taking advantage of the 3-dimensional formability[10].

3. Conclusion

This paper has introduced distinctive soft magnetic materials of the JFE Steel Group, which include JGS, a grain oriented electrical steel with the world's highest orientation sharpness, JNE Core, a new non-oriented electrical steel with an improved balance of magnetic flux density, iron loss, and hardness, Super Core JNEX, which combines low iron loss in the frequency range of 1 kHz–100 kHz and a low noise property resulting from zero magnetostriction, JIP MG270H, an iron powder which enables 3-dimensional shape design, and the soft ferrite cores MB4 core, which is the world's top level low iron loss soft ferrite core, and MBT2 core, which has suppressed temperature dependent behaviours, making it the optimum product for onboard automotive applications. **Figure 8** presents an overview of the main application range of each of these soft magnetic materials from the viewpoint of magnetic flux density and frequency. In the future, expanding the respective coverage of these materials step by step, the JFE Steel Group will

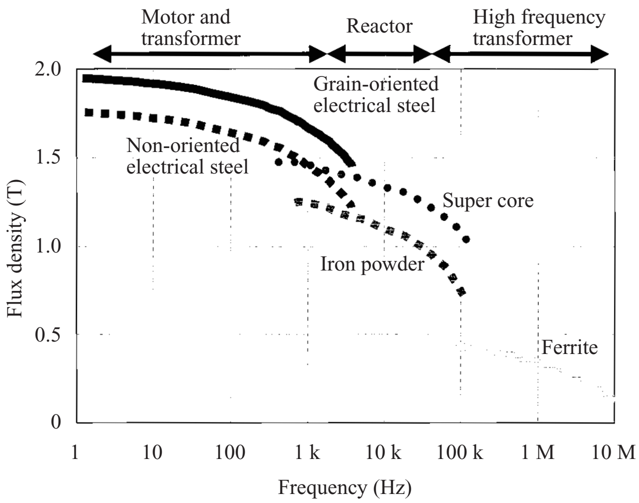


Fig.8 Overview of the main application range of each material

continue to develop new materials both from material properties and from application technologies.

References

1) Morito, N.; Komatsubara, M.; Shimizu, Y. Kawasaki Steel Giho. vol. 29, no. 3, 1997, p. 129.
2) Honda, A.; Obata, Y.; Okamura, S. Kawasaki Steel Giho. vol. 29, no. 3, 1997, p. 136.
3) Honda, A.; Senda, K.; Sadahiro, K. Kawasaki Steel Giho. vol. 34, no. 2, 2002, p. 85.
4) Bozorth, R. M. Ferromagnetism. D. Van Nostrand. 1951.
5) Jitsukawa, M.; Hosoya, Y. NKK Technical Report. no. 179, 2002, p. 36.
6) Ishida, M.; Okabe, S.; Sato, K. Kawasaki Steel Giho. vol. 29, no. 3, 1997, p. 185.
7) Tanaka, Y.; Hiura, A.; Ninomiya, H.; Tsuru, K.; Kobayashi, H.; Masuda, S. NKK Technical Report no. 131, 1990, p. 1.
8) Gotoh, S. Kawasaki Steel Giho. vol. 31, no. 1, 1999, p. 76.
9) Ozaki, Y.; Fujinaga, M. Kawasaki Steel Giho. vol. 31, no. 2, 1999, p. 34.
10) Maetani, T.; UETA, M; Nakamura, N. JFE Steel Giho. no. 7, 2005, p. 24.