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Magnetic Materials in JFE Steel Group

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Abstract:

Since the first production of cold rolled non-oriented electrical steel sheets in 1954, grain oriented electrical steel sheets in 1959 and 6.5% Si steel sheets (Super Core™) in 1993, JFE Steel group has developed various kinds of electrical steels, including iron powder and MnZn ferrite, etc. to meet diversifying needs with a lineup of soft magnetic materials that cover a wide frequency range from commercial frequency to MHz order.

1. Introduction

JFE Steel began producing cold rolled non-oriented electrical steel sheets in 1954 and grain-oriented electrical steel in 1959, and has developed various types of electrical steel sheets since that time. Recently, the company also developed a 6.5% silicon (Si) steel sheet with an increased Si content in the steel, and Si gradient steel sheets with a gradient distribution of Si in the sheet thickness direction. The applications of these electrical steel sheets span a diverse range, including traction motors for hybrid electric vehicles (HEV) and electric vehicles (EV), high efficiency induction motors for industrial applications, large-scale rotating machinery for use in hydro power and thermal power generators, and reactors for solar power generation, and the properties required in these electrical steel sheets are also diversifying.

JFE Steel has also developed insulation-coated iron powder for Soft Magnetic Composite (SMC) cores for electrical equipment which is driven in the frequency range of the several kHz to several 10 kHz order. Because it is possible to manufacture SMC cores with complex shapes and 3-dimensional magnetic paths can also be configured, application to axial gap motors and other motors with special shapes is expected.

On the other hand, with the progress of power semiconductors, higher switching frequencies are being adopted in electronic components, and accompanying this trend, higher frequency noise is also generated. To address this problem, JFE Chemical Corporation developed high resistance, high permeability MnZn ferrite which can remove high frequency noise of the MHz order[1)].

Through the development of these various types of magnetic materials, the JFE Group has created a lineup of soft magnetic materials that covers a wide frequency region from several 10 Hz to several MHz, as shown in **Fig. 1**. This paper presents a brief explanation of the features and applications of these magnetic materials.

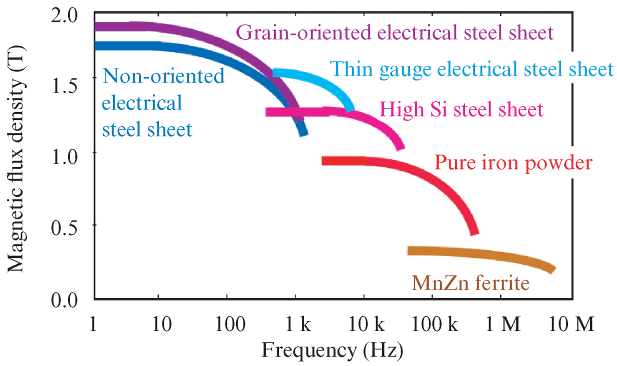

Fig. 1 Applicable range of various soft magnetic materials

2. Electrical Steel Sheets

2.1 Grain-Oriented Electrical Steel

Grain-oriented electrical steel is a type of 3% Si steel which features extremely high magnetic properties in the rolling direction, and is used mainly as a core material for transformers. Because its magnetic properties have a large influence on transformer energy efficiency, it is a material that makes an important contri-

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bution to society through energy saving and CO_2 reduction.

In response to heightened social needs for energy saving in transformers, strict transformer efficiency regulations are now applied in the form of the Top Runner program[2] in Japan, the Department of Energy (DOE) Energy Conservation Standards[3] in the United States and the EcoDesign Directive[4] in the EU. The Top Runner program began from the regulations for specified equipment under Japan's Energy Conservation Act, which were applied to oil immersed transformers in fiscal year 2006. These regulations targeted the world's highest level of energy conversion efficiency of approximately 99%, representing a 30% reduction of loss in comparison with the former JIS product. With the progress of energy-saving technology for transformers, a changeover to the second judgment criteria was mandated from FY 2014, and third criteria are currently under study, suggesting that even higher efficiency will be demanded. To meet social demand for transformer energy saving and reduction of CO_2 emissions, JFE Steel has consistently pursued low iron loss technologies for grain-oriented electrical steel.

The crystallographic features of grain-oriented electrical steel sheets are shown in **Fig. 2**. In steel sheets with a sheet thickness of 0.23 to 0.35 mm, the millimeter-order crystal grains that pass through the sheet thickness form a structure in which the direction of easy axis of magnetization (<001> direction of bcc) is oriented in the rolling direction.

Magnetization of grain-oriented electrical steel sheets is borne by 180° magnetic domains, which display spontaneous magnetization parallel and antiparallel to the easy axis of magnetization, and the boundaries of the domains are divided by magnetic domain walls. AC magnetization of grain-oriented electrical steel sheets in which the magnetic domain width parallel to the direction of magnetization increases or decreases repeatedly by movement of the domain walls,

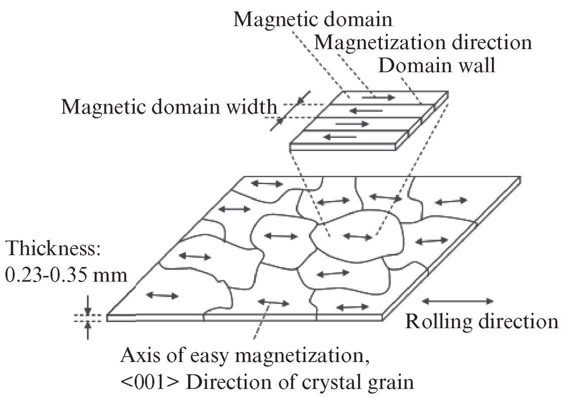

Fig. 2 Schematic diagram of crystallographic and magnetic features of grain oriented electrical steel sheet

and so-called iron loss is the loss that occurs as a result of this domain wall movement. Iron loss consists of hysteresis loss (W_h), classical eddy current loss (W_{cc}) and anomalous eddy current loss (W_{ac}), as shown by Eq. (1).

$$W = W_h + W_{ce} - W_{ae} \quad (1)$$

Because hysteresis loss is caused by obstruction of magnetic domain wall movement by internal precipitates or impurities in the steel sheet, it is desirable to reduce impurity elements such as C, N, O, S, *etc*. to the absolute minimum. Moreover, since magnetization becomes easier and hysteresis loss decreases as the angle between rolling direction and easy axis of magnetization of the crystal grains becomes smaller. Grain-oriented electrical steels are classified as HGO (High induction Grain Oriented steel) or CGO (Conventional Grain Oriented steel) according to their levels of magnetic flux density, which depends on crystal orientation property.

Classical eddy current loss is loss due to eddy current caused by electromagnetic induction by AC magnetization, and can be reduced by reduction of the sheet thickness or addition of Si. The thickness of the grain-oriented electrical steel sheets produced by JFE Steel is 0.23 to 0.35 mm, and the Si content is approximately 3%, considering cold rollability, *etc*.

Anomalous eddy current loss is loss caused by magnetic domain wall motion, and can be reduced by decreasing the magnetic domain width. Refinement of the crystal grain size and increasing tensile stress by applying an insulating film to the steel sheet surface are effective for reducing this type of loss. As techniques for physically reducing the magnetic domain width, the method of introducing local strain in the steel sheet and the method of forming grooves on the steel sheet surface are available.

The former method of introducing local strain is used in stacked transformer cores because the effect of domain refinement is lost due to stress release annealing (so-called non-heat proof domain refinement). JFE Steel produces the "JGSE™" series of products which are excellent in both low iron loss and noise characteristics by a method that effectively introduces local strain, and has earned an outstanding reputation for this product[5].

In the latter method of forming grooves on the sheet surface, JFE Steel applies the heat proof domain refinement method[6] utilizing electrolytic etching. These materials are used in wound transformer cores, which require stress release annealing, under the product series name JGSD™"

Figure 3 shows JFE Steel's current product line-up

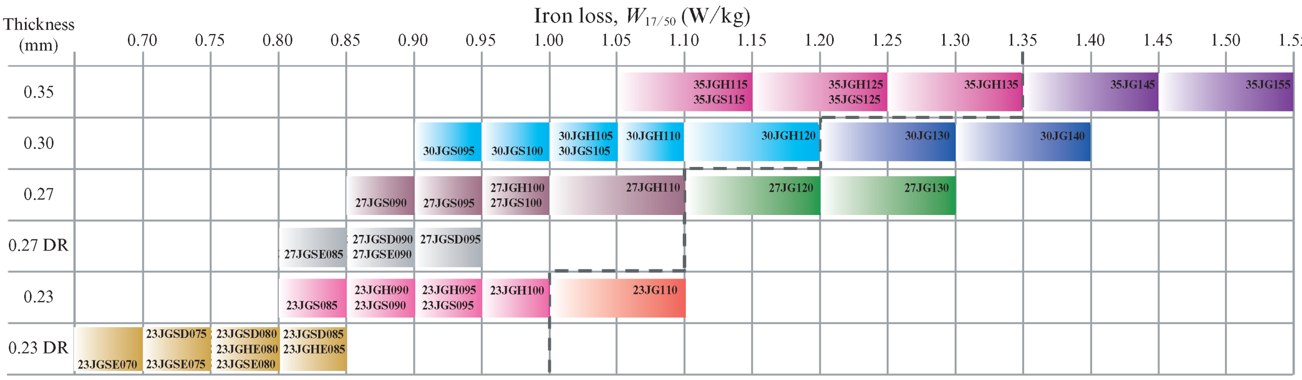

Fig. 3 JFE Steel's product line-up of grain oriented electrical steel sheets

of grain-oriented electrical steel sheets. To respond to the diverse needs of customers, JFE offers six series: "JG", "JGS™", "JGH™", "JGSD™", "JGSE™" and "JGHE™." The "JG" Series is a series of general grain-oriented electrical steel sheets, which are classified as CGO. The JGS™ Series is JFE Steel's highest grade of grain-oriented electrical steel and has extremely high magnetic flux density and low iron loss that surpass those of other companies' products. The JGS™ Series is classified as HGO. Because it has an excellent crystal orientation property, this series is also used to achieve low noise in transformers.

Product names such as "23JGSE070" in Fig. 3 indicate the sheet thickness, steel type and guaranteed value of iron loss ($W_{17/50}$). For example, "23JGSE070" indicates a sheet thickness of 0.23 mm, steel type of JGSE and guaranteed iron loss value of 0.70 W/kg or less.

2.2 Non-Oriented Electrical Steel Sheets

Because motors account for approximately 60% of total electric power consumption in Japan[7], assuming hypothetically that an improvement of 1% in motor efficiency is equivalent to an energy saving equal to the output of one 500 MW nuclear power plant, the development of high efficiency motors has become an urgent issue.

The non-oriented electrical steel sheets which are widely used as the core materials for these motors are functional materials that transmit magnetic energy, and are key materials that control motor efficiency.

In recent years, electric vehicles (EV) market has been rapidly growing. Various properties are required in EV traction motors, including compact size, high efficiency, high torque and reliability, and in order to satisfy those property requirements, the following properties are necessary in the electrical steel sheets that are to be used as core materials.

Because high torque is necessary in vehicle starting and acceleration, high magnetic flux density in the high magnetic field strength region is required in the electrical steel sheets. On the other hand, because the ratio of iron loss in total motor loss is large in the high rotational speed region, low high-frequency iron loss is demanded, and high thermal conductivity is necessary in order to dissipate the generated heat. In addition, in interior permanent magnet motors (IPM motors), high strength and high fatigue strength are also required to prevent scattering of the magnets. Although various properties are required in these electrical steel sheets, it is difficult to satisfy all of these requirements with one type of electrical steel sheet. For this reason, various types of electrical steel sheets are used appropriately, corresponding to the relative importance of the motor performance requirements.

Figure 4 shows an example of the magnetic properties of thin-gauge electrical steel sheets of the JNE™ Series with sheet thicknesses of 0.20 mm, 0.25 mm and 0.30 mm, which are used in EV traction motors[8]. In comparison with the highest grade material (JNE Series) with the thickness of 0.35 mm, iron loss decreases by approximately 25 to 30% in the thin-gauge (0.20 mm) electrical steel sheets, and this tendency

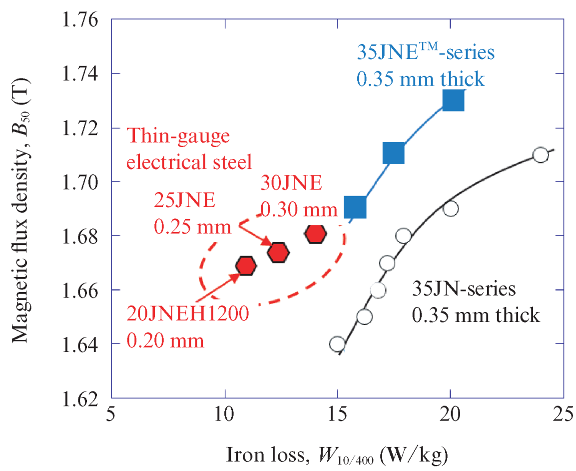

Fig. 4 Magnetic properties of thin-gauge electrical steel sheets

becomes remarkable at higher frequencies.

In EV motor applications, in addition to the thin-gauge electrical steel sheets of the JNE Series, the JFE Steel line-up also includes the JNP™ Series with higher magnetic flux density and the JNT™ Series with improved strength. These materials are used appropriately, corresponding to the property requirements of the application[8].

2.3 High Si Steel Sheets

6.5% Si steel is a material which had been known since the 1950s[9]. It had been found that adding 6.5% of Si to the steel reduces magnetostriction to substantially zero, and the material shows the highest values of magnetic permeability and iron loss. However, if the amount of Si addition is increased, the elongation property of the material decreases dramatically, and it becomes difficult to produce thin-gauge steel sheets by rolling. For this reason, Si addition had been limited to around 3% in conventional high grade electrical steel sheets. To overcome this problem, in recent years JFE Steel developed a production technology for high Si steel sheets by the CVD (chemical vapor deposition) method instead of rolling, enabling mass production of 6.5% Si steel sheets (JNEX™)[10]. Because 6.5% Si steel sheets have remarkably low iron loss in comparison with conventional non-oriented electrical steel sheets, excellent properties as a core material for high speed motors can be expected[11].

More recently, JFE Steel also developed Si gradient magnetic materials (JNHF™ Series), in which a gradient Si concentration is applied in the sheet thickness direction by using the CVD process [12,13]. The JNHF Series not only has iron loss properties superior to those of JNEX in the high frequency range of 10 kHz and higher, but also has the merits of high magnetic flux density and excellent formability such as punching performance, *etc*., because the Si content in the sheet center-of-thickness is low compared to that of JNEX[13].

The JNEX Series and JNHF Series have low iron loss at high frequencies and thus can contribute to high efficiency in EV traction motors. However, since their magnetic flux density was low compared to that of general non-oriented electrical steel sheets, decreased motor torque was an issue. Therefore, JFE Steel developed the JNRF™ Series with improved magnetic flux density, while continuing to use eddy current loss reduction technology, based on the technology for applying a Si gradient in the sheet thickness direction[14].

Figure 5 shows the magnetic properties of the JNRF Series. In comparison with the JNHF Series, the JNRF Series has low iron loss at 400 Hz, which is equivalent to the drive frequency of EV traction motors, and displays a significantly higher magnetic flux density. Based on these features, the JNRF Series can be expected to contribute to high torque and high efficiency in EV traction motors.

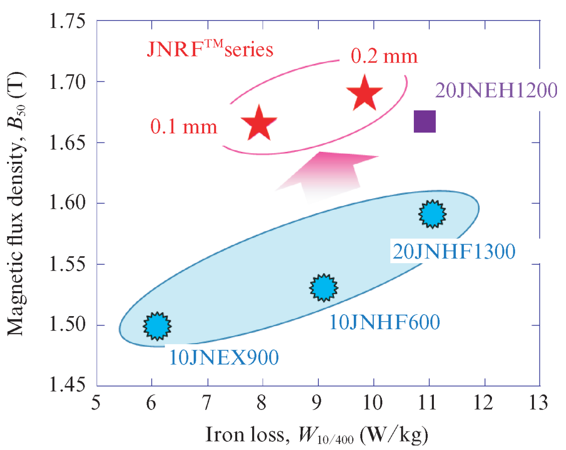

Fig. 5 Magnetic properties of Si gradient steel sheets

3. Soft Magnetic Composite (SMC) cores

SMC cores are magnetic cores which are produced by compacting insulation -coated soft magnetic powder such as pure iron powder, Fe-Si powder and Fe-Si-Al powder (**Fig. 6**). The microstructure of an SMC core is shown in **Fig. 7**. The insulation coating which is coated on the particle surface remains between the soft magnetic particles even after compaction and annealing, resulting in a structure in which a metal phase with

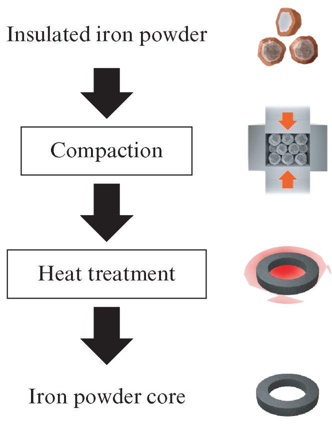

Fig. 6 Production process of iron powder core

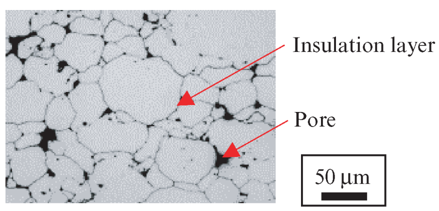

Fig. 7 Microstructure of iron powder core

high saturation magnetic flux density is finely divided by an insulation layer with high electrical resistance. Owing to this microstructure, SMC cores simultaneously satisfy both high saturation magnetic flux density in comparison with ferrite cores, and low eddy current loss in comparison with electrical steel sheets[15]. In addition, because SMC cores have good DC superposition characteristics, they are increasingly used in applications that require a combination of high saturation magnetic flux density and low eddy current loss, such as reactors[16].

As another distinctive feature of SMC cores is a combination of ease of near-net shape molding as a derivative of powder metallurgy technology, and 3-dimensionally isotropic magnetic properties. Thanks to this feature, it is easy to manufacture motors in which cores with complex geometries as well as 3-dimensionally isotropic magnetic properties are required, such as axial gap motors[17] and claw teeth motors[18]. Since one merit of these motors with complex core shapes is compact motor size, they are expected to be used in applications such as in-wheel motors[19], where space constraints make it difficult to apply conventional radial gap motors (motors in which the core manufacturing method involves punching and then stacking electrical steel sheets). Seen from a different viewpoint, this feature of "downsizing in comparison with conventional motors is possible," which is an advantage of above-mentioned motors with special shapes, also means "it is possible to achieve higher power with the same motor size." Focusing on this feature of "higher power," axial gap motors have been adopted in some sports models of hybrid electric vehicles[20]. As described above, SMC cores are expected to contribute to electrification of applications that had been difficult with conventional motors.

Among the applications of SMC cores, particularly in order to respond to the needs of axial gap motors and other motors with special shapes, JFE Steel commercialized a product called "Denjiro™," which is an insulation-coated pure iron powder for SMC motor cores. The production process of "Denjiro" is shown in **Fig. 8**. The pure iron powder which forms the base of "Denjiro" is produced by the water atomization method, and the particle shape and size, which are critical factors that determine the magnetic properties of a SMC core, are controlled in this process. Next, decarburization and deoxidation heat treatment are carried out under a wet hydrogen atmosphere is introduced, and finally, insulation coating is applied to the particle surface. The resulting product is the insulation-coated pure iron powder "Denjiro." The external appearance of particles of JFE Steel's pure iron powder for powder metallurgy, JIP™ 304AS, and Denjiro are shown in **Fig. 9**. In comparison with JIP 304AS, Denjiro's particle shape is spherical, as this feature reduces strain during compaction and achieves low iron loss in SMC cores. The iron losses of SMC cores manufactured by compacting JIP 304AS with an insulation coating and Denjiro at a pressure of 980 MPa, followed by heat treatment in a nitrogen atmosphere at 600°C are shown in **Fig. 10**. In comparison with the SMC core using JIP 304AS, the core using Denjiro achieves low iron loss at all frequencies.

This section has described the advantages of SMC cores and JFE Steel's new product Denjiro. Although only one grade of Denjiro has been commercialized at

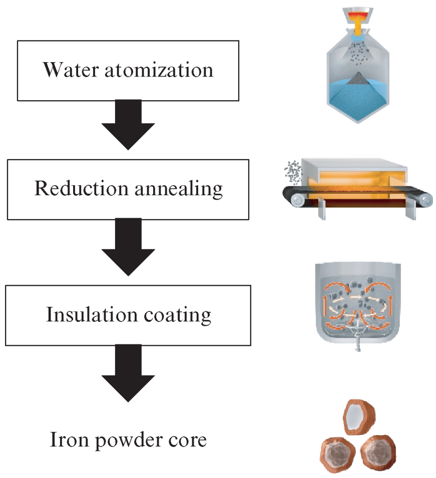

Fig. 8 Production process of Denjiro™

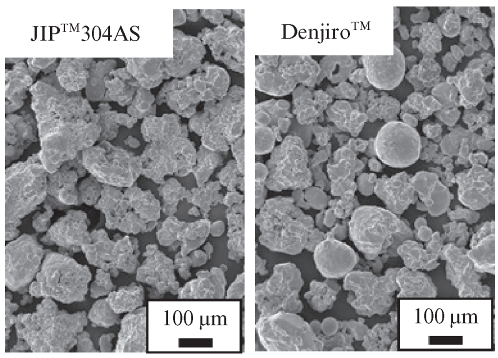

Fig. 9 Powder particle shapes of JIP™ 304AS and Denjiro™

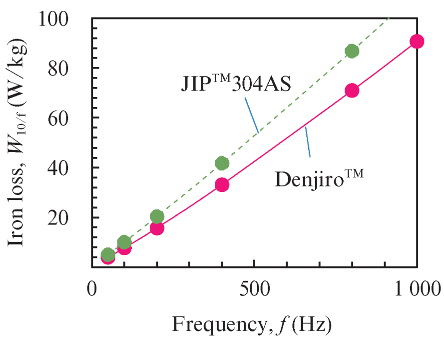

Fig. 10 Iron loss of Denjiro™

present, JFE plans to expand this line-up in the future, corresponding to the needs of customers.

4. MnZn Ferrite

4.1 Features of MnZn Ferrite

Ferrite is a general term[21] for Fe-based oxide magnetic materials. Among the ferrites, MnZn ferrite and NiZn ferrite may be mentioned as representative examples of soft magnetic materials. The typical magnetic properties of these two ferrites are shown in **Table 1**. The features of MnZn ferrite are a high saturation magnetic flux density B_m, low iron loss and high initial permeability μ_i. On the other hand, NiZn ferrite has high resistivity ρ and an electrical insulation property, and also has good frequency characteristics owing to its high f_r, which is the attenuation frequency of μ_i.

JFE Chemical Corporation and JFE Ferrite Co., Ltd., which are JFE Steel Group companies, manufacture and sell MnZn ferrite sintered cores (hereinafter, sintered cores). The raw material used in these products is high purity iron oxide obtained as a byproduct when the waste acid from surface pickling in the steel sheet manufacturing process is recovered and recycled. These sintered cores are produced at three production centers located in Japan, Thailand and China.

The various properties of MnZn ferrite in comparison with other metal magnetic materials are shown in **Fig. 11**. Because MnZn ferrite is a ferrimagnetic substance[22], its Curie temperature T_c and saturation magnetic flux density B_m are inferior to those of the metal magnetic materials. However, as an oxide, its ρ is $10^{5\sim8}$ times higher, which means it is possible to suppress eddy current loss. Therefore, in comparison with the metal magnetic materials, it has the features of low loss and high μ_i in the high frequency range of 10 k to 1 MHz, as shown in **Fig. 12**.

4.2 Production Process of MnZn Ferrite

The general production process of MnZn ferrite is shown in **Fig. 13**, and an image of the crystallographic microstructure of a sintered core is shown in **Fig. 14**. Although most of magnetic properties are substantially determined by the composition ratio of the main raw materials, some properties are affected by the microstructure of the polycrystal structure. After manganese oxide and zinc oxide powders are mixed with the high purity iron powder which is the main raw material, the composition is homogenized by calcining at approximately 900°C. Wet pulverizing treatment to a size of about 1 μm is performed to uniformly increase the reactivity of the obtained calcined powder in the sintering process. In the pulverizing process, trace components with features such as segregation to the grain boundaries, *etc.* are frequently added to control the

Table 1 List of comparison of properties between MnZn and NiZn ferrite

	B_m@23°C (MHz)	μ_i@10 kHz 23°C	ρ (Ωcm)	f_r (MHz)
MnZn ferrite	400 ~ 550	2 000 ~ 15 000	~ 10^3	0.1 ~ 2
NiZn ferrite	250 ~ 500	~ 2 000	10^8 ~	~ 10

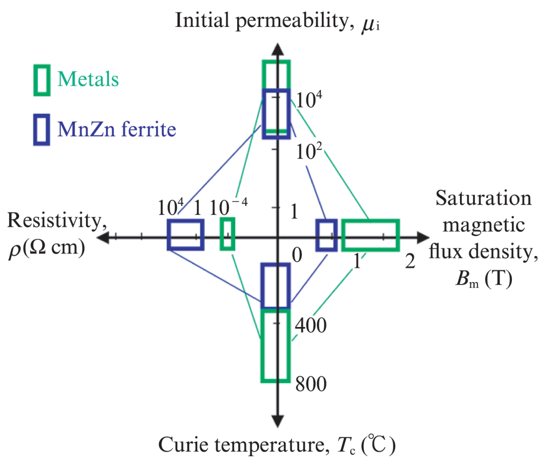

Fig. 11 Comparison of properties between MnZn ferrite and metal magnetic materials

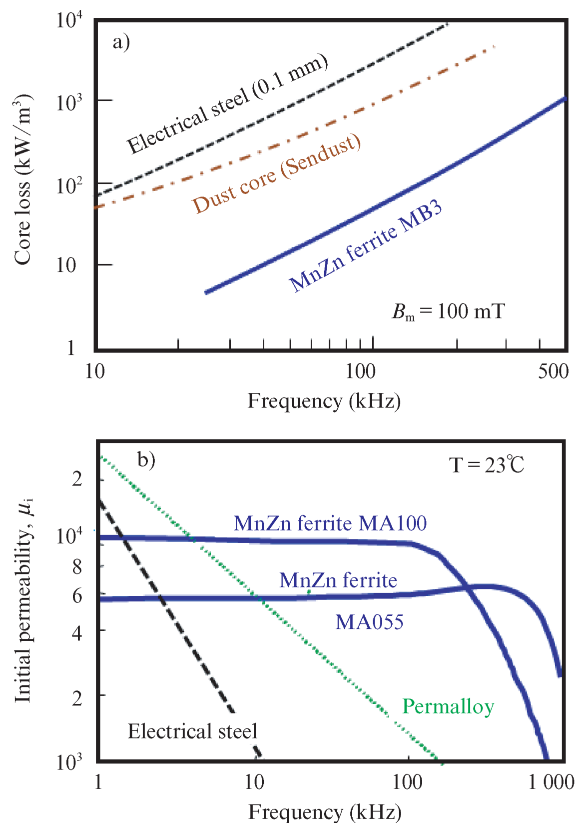

Fig. 12 Comparison of frequency characteristics between MnZn ferrite and metal magnetic materials
a) Iron loss, b) Initial permeability

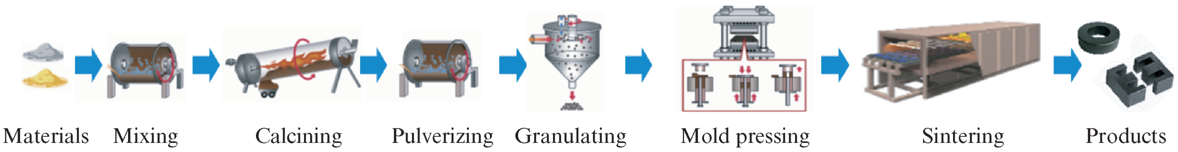

Fig. 13 General manufacturing process of MnZn ferrite

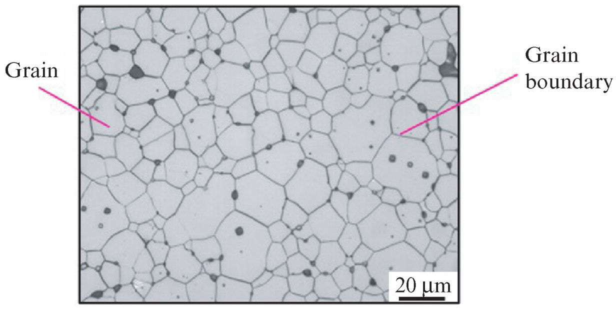

Fig. 14 Image of microstructure of MnZn ferrite sintered core

crystallographic microstructure to improve magnetic properties. After pulverization, the material is in a slurry state. An aqueous solution of polyvinyl alcohol (PVA) or some other water-soluble resin, which plays the role of a binder, is mixed with this slurry, and spray granulation is performed by the spray drying method. Due to surface tension, the sprayed slurry takes a spherical shape. This shape is retained as-is during drying by the adhesive force of the binder, forming a spherical granulated powder with high flowability. The granulated powder is then filled in a mold, and a molded compact is formed by powder compacting to the desired shape at a pressure of 100 MPa or more. Finally, sintered core products of MnZn ferrite with excellent magnetic properties are obtained by solid phase sintering by applying heat with a temperature of 1 200°C or higher under a controlled atmosphere using a sintering furnace.

4.3 Applications of MnZn Ferrite

The main applications of sintered cores can be broadly classified into two types, magnetic core materials for transformers and for noise filters.

The drive frequency of the core materials of the power conversion transformers of switching power supplies is generally around 100 kHz, and as noted previously, MnZn ferrite is superior to metal magnetic materials in terms of low loss. Thus, assuming transformers that obtain the same output, the drive frequency and the cross-sectional area of the transformer have an inversely proportional relationship[23]. This means the size and weight of the device can be reduced by using MnZn ferrite. The property requirements for the MnZn ferrite used in this application are low loss, a high Curie temperature T_c and a high saturation magnetic flux density B_m. In the on-board automotive applications described below, materials with low loss under a wide temperature range, such as the MBT1[24] shown in **Fig. 15**, are generally superior.

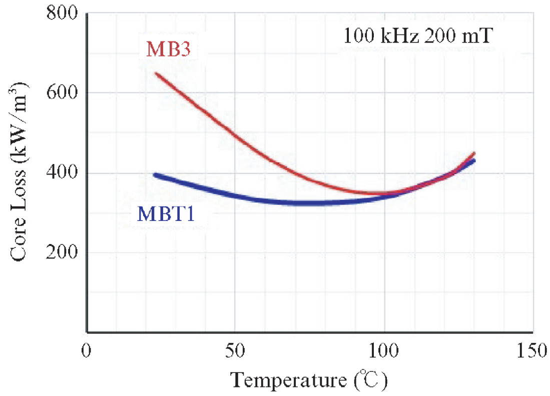

Fig. 15 Temperature dependence of iron loss of MnZn ferrite

The harmonic noise component superimposed on a circuit signal has a frequency several times higher than the drive frequency, but due to concern that this noise component may induce mis-operation of the equipment, a noise filter is used to remove it. The AC resistance of a circuit has a proportional relationship to the product of the inductance component of the core and frequency. Noise filters utilize this principle to selectively remove high frequency noise from signals by using the inductance component of the core. The property requirements for the MnZn ferrite used in this application are a high μ_i, which has a proportional relationship with inductance, and good frequency characteristics of μ_i, in order to remove noise over a wide range of frequencies. In on-board automotive applications, MnZn ferrite provides both the superior properties of a high Curie temperature T_c, which is important in terms of high temperature durability, and a high saturation magnetic flux density B_m, which is needed to prevent magnetic saturation.

Conventionally, the main type of final products of sintered cores were electrical equipment. Recently, however, there has been a progressive shift to hybrid electric vehicles (HEV) and electric vehicles (EV) in automotive drive systems, and in an increasing number of cases, the final use of sintered cores is now in automobiles. For on-board automotive applications, it is necessary to consider vibration, *etc.* during travel.

Therefore, in addition to good magnetic properties, importance is also attached to high strength in sintered cores. Accompanying the further popularization of HEV/EV in the future, increased demand for sintered cores for on-board applications is considering a certainty. With the support of JFE Steel, JFE Chemical is studying methods for achieving higher strength in sintered cores[25], and is promoting the development of sintered cores with both high strength and excellent magnetic properties, together with the establishment of stable manufacturing conditions.

5. Conclusion

This paper has presented a brief overview of the features and applications of grain-oriented electrical steel sheets, non-oriented electrical steel sheets, high Si steel sheets, insulation-coated iron powder for use in Soft Magnetic composite cores and MnZn ferrite, which are magnetic materials produced by the JFE Group. In the future, with the progress of efforts to achieve carbon neutrality, electrification is expected to accelerate, and even higher needs for small size and high efficiency in electrical equipment are foreseen. The JFE Group intends to develop new magnetic materials that respond to the increasingly diverse requirements of customers, and will propose use technologies that make it possible to demonstrate their material properties to the fullest possible extent.

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