JFE TECHNICAL REPORT
No. 21 (Mar. 2016)

Recent Development of Non-Oriented Electrical Steel in JFE Steel†

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Abstract:

Since the first production of cold rolled non-oriented electrical steel strip in 1954, JFE Steel has developed various kinds of electrical steels for use as a core material for motor applications. In recent years, the application of this material ranges from automobile usage such as hybrid electric vehicle (HEV)/electric vehicle (EV) traction motors for vehicles to appliances and other applications such as electric power steering motors, high efficiency air-conditioner compressor motors, vacuum cleaner motors, energy efficient induction motors, and hydraulic/thermal power generators. Responding to customer demands, JFE Steel has further diversified properties of cold rolled non-oriented electrical steel sheets. In this paper, we introduce distinctive products such as the JNE™ series for energy efficient motors, the JNP™ series for high torque motors, the JNEH™ series for high frequency motors as well as the JNT™ series for high speed rotors.

1. Introduction

Motors account for approximately 60% of electric power consumption in Japan[1)]. Assuming motor efficiency is improved by 1%, this would be equivalent to an energy saving equal to one 500 000 kW class nuclear power plant. Therefore, the development of energy efficient motors is an urgent challenge.

Non-oriented electrical steel sheets, which are widely used as iron core materials for these motors, are functional materials that transmit magnetic energy, and thus are a key material that determines motor efficiency. Because motor efficiency increases as the iron loss of electrical steel sheets decreases, and torque increases as magnetic flux density increases, electrical steel sheets which provide both low iron loss and high flux density are now demanded. Moreover, in addition to magnetic characteristics, an excellent blanking property, dimensional accuracy after blanking, electrical resistance by coating, corrosion resistance, excellent weldability, strict sheet thickness accuracy and other properties are also required in electrical steel sheets for use in motors.

JFE Steel began manufacturing cold-rolled non-oriented electrical steel sheets in 1954. Thereafter, as low iron loss materials, the company developed 50RM270 utilizing high purification technology in 1978 and also developed 50RM250 in 1983. As high flux density materials, in 1985, the company developed the RP Series with higher flux density by texture control. The company also commercialized the RMA™ Series, which satisfies both low iron loss and high flux density after stress-relief annealing.

After 1990, the requirements for electrical steel sheets also diversified accompanying the trend toward energy efficiency in motors for household electrical appliances and the popularization of hybrid electric vehicles. JFE Steel was among the first to develop new electrical steel sheets which responded to those needs, developing the JNE™ Series with an outstanding balance of flux density and iron loss for use in energy efficient motors, the JNEH™ Series of thin-gauge electrical steel sheets with low high-frequency iron loss for use in

† Originally published in *JFE GIHO* No. 36 (Aug. 2015), p. 6–11
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high frequency motors, the JNP™ Series with high flux density for high torque motors and the JNT™ Series with high strength for rotors of high speed motors.

This paper describes the features of these electrical steel sheets and introduces examples of their applications.

2. Electrical Steel Sheets for HEV/EV Motors

2.1 Properties Required in HEV/EV Motors and Core Materials

Since the world's first mass-production hybrid electric vehicle (HEV) was sold in Japan in 1997, the number of units produced has increased annually, and recent years have seen a further increase in demand due to the sharp rise in the price of crude oil and heightened awareness of protection of the global environment. When originally developed, fuel economy was the strong point of HEV. More recently, however, HEV which offer not only fuel economy, but also excellent motor response and an enjoyable driving experience taking advantage of initial torque have been developed. **Figure 1** shows the performance required in HEV traction motors and core materials[2)]. Because high torque is necessary when starting and accelerating, high magnetic flux density is required in electrical steel sheets used as core materials. On the other hand, when motor speed is high, the proportion of iron loss in motor loss becomes large. Therefore, material with low high-frequency iron loss is demanded, and high thermal conductivity is also necessary in order to release the generated heat. Furthermore, in interior permanent magnet (IPM) motors, in which magnets are inserted in slots in the motor, high strength and high fatigue strength are demanded to prevent the magnets from flying out of the motor.

As outlined above, a diverse range of characteristics are required in electrical steel sheets, but because it is difficult to satisfy all of these requirements with a single type of electrical steel sheet, respective types of electrical steel sheets are used appropriately corresponding to the degree of motor performance requirements. This paper introduces the properties of electrical steel sheets for energy efficient motors, which possess an excellent balance of flux density and iron loss, thin-gauge electrical steel sheets with low high-frequency iron loss, high flux density electrical steel sheets for use in high torque motors and high strength electrical steel sheets.

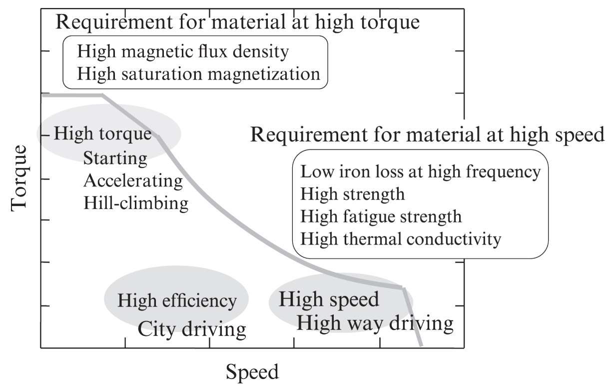

Fig. 1 Demands for hybrid electric vehicle (HEV) motors and core materials

2.2 Electrical Steel Sheets for Energy Efficient Motors: "JNE™"

In the traction motor core materials of hybrid electric vehicle/electric vehicle (HEV/EV), low iron loss is required for high motor efficiency, and high magnetic flux density is required for motor downsizing and high torque. In order to reduce the iron loss of electrical steel sheets, Si addition is effective from the viewpoints of increasing resistivity and decreasing magnetic anisotropy, and approximately 3% Si is added to high grade electrical steel sheets. On the other hand, because Si is a nonmagnetic element, flux density decreases due to a decrease in saturation magnetization. For this reason, it was difficult to manufacture materials with both high flux density and low iron loss characteristics by the conventional technique of Si addition. To overcome this

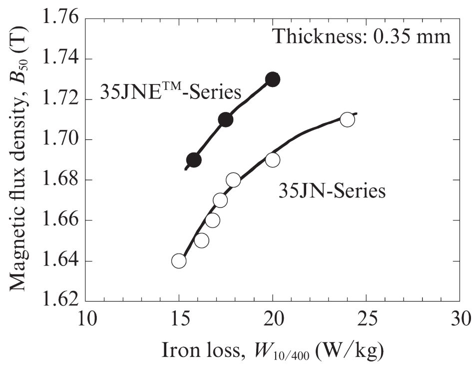

Fig. 2 Magnetic properties of non-oriented electrical steel sheets for energy efficient motor

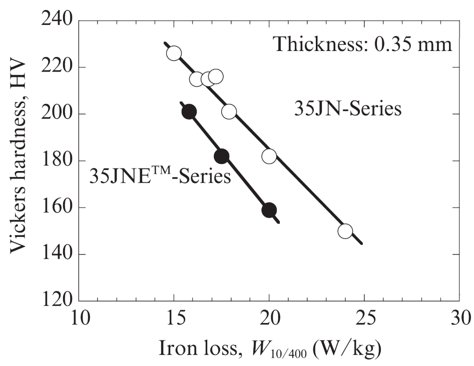

Fig. 3 Vickers hardness of non-oriented electrical steel sheets for energy efficient motor

problem, the amounts of addition of Si, Al and other alloy elements were optimized, and it was attempted to increase the (100) and (110) textures, which are favorable for magnetic characteristics, and also to reduce the amount of impurities in the steel[3,4].

Figure 2 shows the magnetic flux density-iron loss balance of the JNE™ Series in comparison with the JN Series, which is the conventional material[2]. The JNE Series has an excellent balance of magnetic flux density and iron loss in comparison with the conventional material, and thus can make an important contribution to high motor efficiency. **Figure 3** shows the Vickers hardness of the JNE Series. In comparison with JN Series products having the same iron loss, the JNE Series has lower hardness, and therefore has the merit of reducing die wear during blanking.

Because the JNE Series not only can contribute to high motor efficiency, but is also advantageous from the viewpoint of productivity, as described above, this series is already widely used in commercial HEV, etc.

2.3 Electrical Steel Sheet for High Torque Motors: "JNP™"

In the traction motors of HEV/EV, large torque is required during starting, hill-climbing and accelerating. Therefore, a further increase in magnetic flux density is desirable in electrical steel sheets which are used as iron core materials. Against this background, JFE Steel developed the JNP™ Series, which offers higher flux density than the conventional materials[5]. The flux density-iron loss balance of the developed materials is shown in **Fig. 4**. The magnetic flux density of the JNP Series at the same iron loss has been increased by approximately 0.02 T in comparison with the JNE™ Series.

In this JNP Series, the amounts of addition of Si, Al, Mn, and other alloy elements were optimized and use of grain boundary segregating elements and intermediate process optimization technologies, etc. were applied in order to achieve high magnetic flux density by texture control.

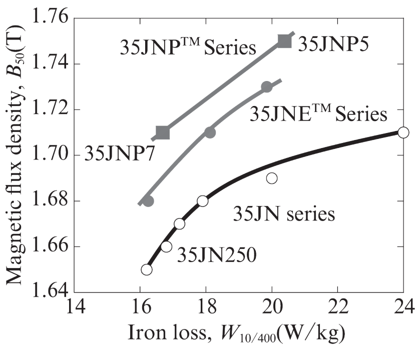

Fig. 4 Magnetic properties of JNP™ series

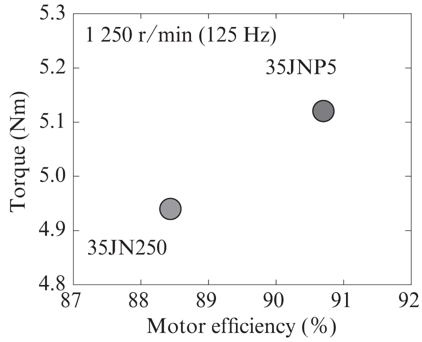

Fig. 5 Motor properties of 35JNP5 used for the direct drive motor

Because the developed material has high magnetic flux density, it is considered a promising material for HEV/EV motor core materials, in which high torque is particularly required, and has already been adopted in commercial HEV motors.

Due to its high flux density, this material is considered suitable for motors in which high torque is required. Electric vehicle motors in which this kind of high torque is required also include direct-drive in-wheel motors[6]. This method has the merit of increasing the degree of freedom in design, in that the space in the vehicle can be widely used and space for batteries can be secured under the seats, and thus is considered to be a promising drive system, especially for compact vehicles.

High torque is demanded in direct-drive motors because they rotate the tires directly without transmission through gears. Moreover, in comparison with motors that rotate at high speed by using gears, direct-drive motors also have the advantage that the percentage of iron loss in motor loss is small because the speed of rotation is low. Based on these points, in electrical steel sheets for use in direct-drive motors, high flux density is a more important requirement than low iron loss.

In order to confirm the superiority of the developed materials in direct-drive motors, an IPM type in-wheel motor with an output of 1.6 kW was manufactured, and its motor characteristics were evaluated. **Figure 5** shows the motor efficiency and torque at a motor speed of 1 250 rpm (equivalent to the vehicle speed of 60 km/h)[5]. From this, both torque and motor efficiency were improved with 35JNP5 in comparison with 35JN250, which was used as a comparison material. Thus, the JNP Series is considered to be a suitable core material for high torque motors such as direct-drive motors, etc.

2.4 Thin-Gauge Electrical Steel Sheet for High Frequency Use: "JNEH™"

In HEV motors, an increase in maximum motor speed is expected in the future from the viewpoint of motor downsizing[7], and it is thought the excitation fre-

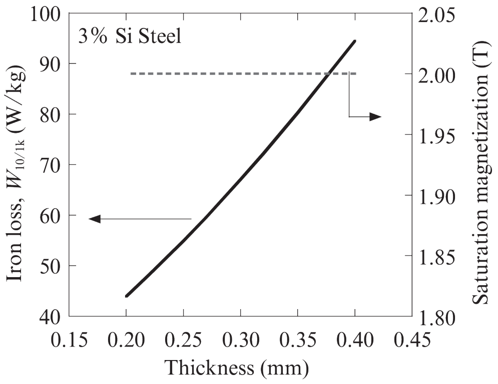

Fig. 6 Effect of thickness on iron loss and saturation magnetization

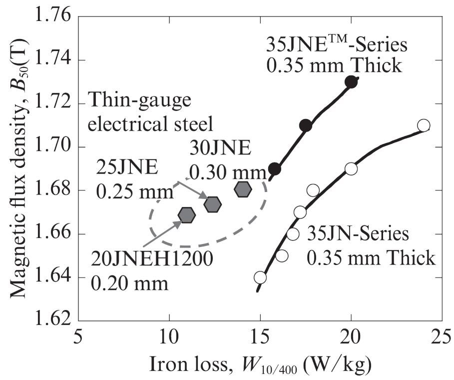

Fig. 7 Magnetic properties of thin-gauge electrical steel sheets

quency of electrical steel sheets which used as core materials will also increase. Furthermore, in case of high speed travel under mainly on the engine power, the motor runs in no-load condition, but in motors that use permanent magnets, high-frequency iron loss occurs due to the alternating magnetic field, and this causes deterioration of fuel economy. Therefore, in electrical steel sheets, increasingly strong demands for reduction of high-frequency iron loss are foreseen. Although iron loss in electrical steel sheets consists of hysteresis loss and eddy-current loss, of these, eddy-current loss increases rapidly due to high frequency magnetic excitation as it is proportional to the square of frequency, as shown in Eq. (1)[8].

$$W = (\pi B_m f t)^2 / 6\rho \quad \text{(1)}$$

where, B_m: Magnetic excitation flux density, f: Frequency, t: Sheet thickness and ρ: Resistivity.

In order to reduce eddy-current loss, the two techniques of reducing sheet thickness and increasing resistivity are conceivable. However, reduction of sheet thickness is more effective because, as shown in Eq. (1), eddy-current loss is proportional to the square of sheet thickness. Moreover, it can also be said the reduction of sheet thickness is a desirable technique for reduction of high-frequency iron loss because this approach does not deteriorate the saturation magnetization, as shown in **Fig. 6**. The development of thin-gauge electrical steel sheets was carried out based on these considerations[9].

Figure 7 shows an example of the magnetic properties of thin-gauge electrical steel sheets. In comparison with the highest grade material having a sheet thickness of 0.35 mm, iron loss is reduced by approximately 20–30% in thin-gauge materials, and this tendency becomes remarkable at higher frequencies. The effect of reduction of high-frequency iron loss by use of thin-gauge electrical steel sheets is not limited to improvement of efficiency, but because motor heat generation decreases. Therefore, the thermal load on the permanent magnets also decreases, and use of magnets which do not contain dysprosium (Dy) and other expensive rare earth elements is also considered possible.

2.5 High Strength Electrical Steel Sheets for Rotor Use: "JNT™"

In the rotors of IPM motors, permanent magnets are embedded in the slot of the rotor, as shown in **Fig. 8**, and during high speed rotation, large stress acts on the bridge due to the centrifugal force of the magnets. From the viewpoint of rotor strength, expanding the width of the bridge would be desirable, but in this case, the leakage flux of the permanent magnets increases, and this reduces motor efficiency. Therefore, the bridge width is designed to be as narrow as possible within the range acceptable for the rotor strength. For this reason, strength capable of withstanding the centrifugal force during high speed rotation and fatigue strength corresponding to repeated loading is necessary in electrical steel sheets used as rotor materials[7]. Moreover, particularly in motors with concentrated winding, iron loss caused by high frequency occurs at the rotor surface; low high-frequency iron loss is also necessary in this case. As high strength electrical steel sheets for rotor use of this type, JFE Steel developed 35JNE-S and 35JNT590T, as shown in **Fig. 9** and **Table 1**. Technologies for realizing high strength, such as solute strength-

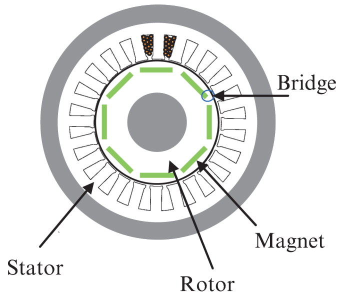

Fig. 8 Schematic diagram of interior permanent magnet (IPM) motor

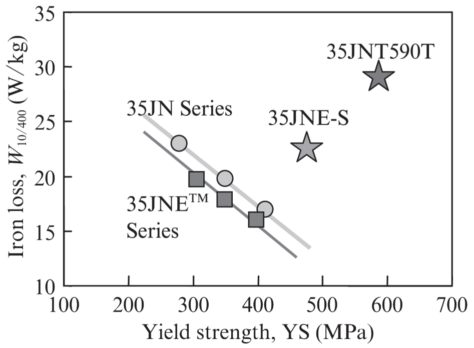

Fig. 9 Magnetic and mechanical properties of high-strength electrical steel sheets

Table 1 Magnetic and mechanical properties of high-strength electrical steel sheets

Grade	Iron loss, $W_{10/400}$ (W/kg)	Magnetic flux density, B_{50} (T)	Yield strength, YS (MPa)	Tensile strength, TS (MPa)	Vickers hardness, HV
35JN250	17	1.67	397	517	213
35JNE-S	23	1.69	480	570	205
35JNT590T	29	1.64	590	640	220

ening, grain refinement, etc. were applied in these materials, and as a result, strength increases of approximately 20% in 35JNE-S and approximately 50% in 35JNT590T were achieved in comparison with the conventional materials.

Application of these materials as rotor materials can contribute to motor downsizing by increasing the maximum rotational speed of the motor and to higher efficiency by suppressing leakage flux as a result of decreasing the width of the rotor bridge.

3. Electrical Steel Sheets for EPS Motors

In addition to the traction motors of HEV/EV described above, electric power steering (EPS) is a new field for automotive motors. It has been reported that EPS improves fuel economy by approximately 3–5% in comparison with hydraulic power steering[10,11]. This is because the hydraulic pump in conventional hydraulic power steering systems operates at times other than actual steering operations such as cornering and the like, thereby consuming energy wastefully, for example, when the vehicle is traveling in a straight line on an expressway, but in contrast to this, with EPS, the motor is driven only during steering operations, and no energy loss occurs while traveling in a straight line. Because fuel economy is largely improved by installation of EPS, the global market for EPS is expected to grow to 65.5 million units by the year 2020, or an increase of 1.9 times in comparison with 2012 [12].

On the other hand, when EPS is used, the problem of poor steering feeling in comparison with hydraulic power steering has been pointed out[13]. This is due to generation of torque (loss torque) during motor idling, and is caused by mechanical friction such as bearing loss, brush loss, and the hysteresis loss of the core material. **Figure 10** shows the relationship between the loss torque of a motor and the hysteresis loss of electrical steel sheets when various types of electrical steel sheets are used in a direct current (DC) brush motor applied in an EPS motors, and indicates that loss torque is decreased by reducing hysteresis loss[2].

Because the hysteresis loss of electrical steel sheets for use in energy efficient motors is small, these materials are considered effective for reducing the loss torque of EPS motors. **Figure 11** shows the results of a comparison of the hysteresis loss of the JN Series and the JNE™ Series[2]. The JNE series has lower hysteresis loss in comparison with the JN Series, and thus is suitable as a core material for EPS motors. To confirm the effect of reducing loss torque of EPS motors using the JNE Series, DC brush motors were fabricated and loss torque was evaluated. The results are shown in **Fig. 12** [14]. Here, loss torque is shown as a ratio when the value of

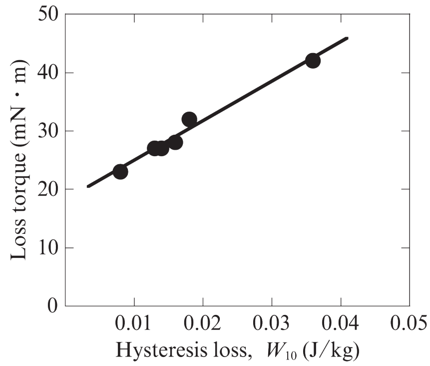

Fig. 10 Relationship between hysteresis loss of core materials and loss torque of electric power steering (EPS) motors

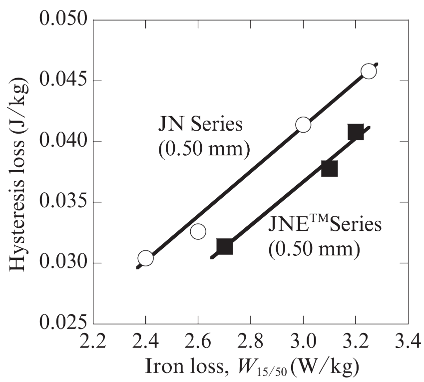

Fig. 11 Hysteresis loss of non-oriented electrical steel sheet for energy efficient motors

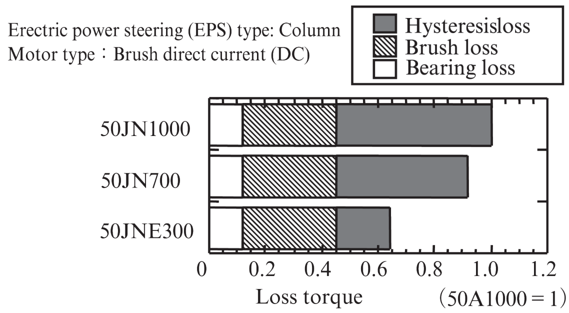

Fig. 12 Loss torque of JNE™ series used for the EPS motor (Loss torque is normalized by the value of 50JN1000)

50JN1000 is 1. Based on the fact that hysteresis loss is greatly reduced in the JNE Series, the possibility of reducing loss torque could be confirmed. As the same effect was also confirmed with the JNP™ series, the JNE Series and JNP Series have been widely adopted in EPS motors.

4. Electrical Steel Sheets for Household Appliances and Industrial Machinery

As air conditioners account for 25% of electric power consumption in Japanese homes[1] and are the product with the largest CO_2 emissions in general households, energy saving is strongly demanded. Since 2006, the energy saving performance of air conditioners has been displayed by the annual performance factor (APF). The factor is an index that shows the efficiency when an air conditioner is used through a period of 1 year under certain conditions[15]. In APF efficiency, the contribution in case the compressor motor rotates slowly in a steady condition is greater than the contribution in case the compressor motor is used at a high rotation speed, for example, during rapid cooling, rapid heating, etc. Therefore, in the electrical steel sheets used as core materials, materials with excellent magnetic properties around commercial frequency are demanded.

Other motors in which priority is given to commercial frequency in the same way as air conditioners include induction motors which are used in industrial applications. Induction motors account for 90% of the number of motors produced in Japan, and diffusion of this type of motor has reached approximately 100 million units[16]. Thus, it can be said that improving the efficiency of induction motors is extremely meaningful for reducing energy consumption. To promote the diffusion of energy efficient induction motors, three-phase induction motors were designated as an object of the Top Runner standards in 2011[17], and Top Runner regulation under the IE3 (Premium Efficiency) standard began in April 2015.

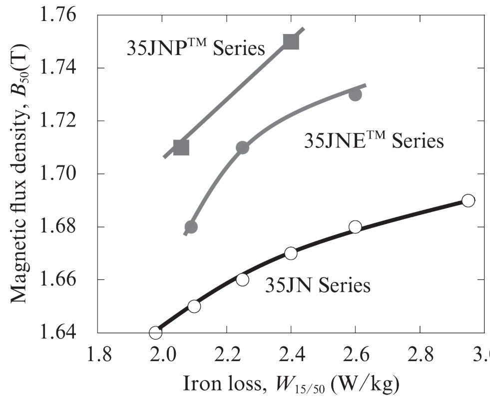

Fig. 13 Magnetic properties of JNE™ series and JNP™ series in commercial frequency

Motor loss can be generally divided into copper loss, iron loss, and mechanical loss. However, since the ratio of copper loss is comparatively high in induction motors, unlike permanent magnet type motors[18], both low copper loss and low iron loss are important. Therefore, in electrical steel sheets used as iron cores, in addition to low iron loss, high magnetic flux density is also strongly demanded from the viewpoint of reduction of copper loss[19].

Figure 13 shows the magnetic properties at 50 Hz of various materials with the same sheet thickness of 0.35 mm. As the JNE™ Series for energy efficient motors and the JNP™ Series for high torque motors both have an excellent flux density-iron loss balance, it can be said that these are suitable as motor core materials for air conditioner compressors and energy efficient induction motors.

5. Electrical Steel Sheets for Large-Scale Generators

Accompanying increasing demand for electric power in recent years, a large number of power plants have been constructed. In particular, following the Great East Japan Earthquake of 2011, demand for hydro and thermal power generation increased, and there was a trend toward larger capacity and higher efficiency in large-scale generators[20].

Ultra-low iron loss at commercial frequency is demanded in the core materials of large-scale generators. Because impurities, grain size, and texture are known to be factors that control the iron loss of electrical steel sheets, ultra-low iron loss has been achieved by controlling these factors. The following technologies are the key points for achieving ultra-low iron loss: (1) Reduction of precipitates and inclusions by high purification of steel, (2) optimization of grain size and composition, and (3) texture control by control of the grain size before cold rolling.

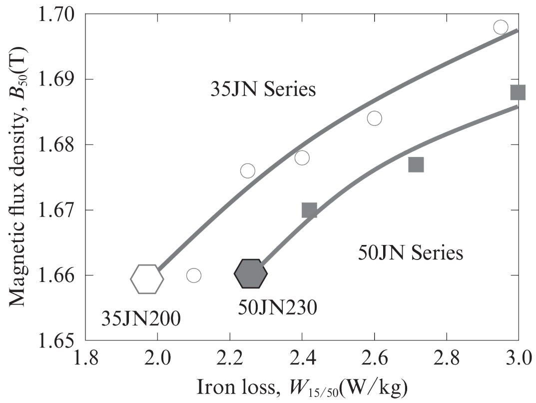

Fig. 14 Magnetic properties of generator core materials

The magnetic properties of 50JN230 and 35JN200, which were developed by using these technologies, are shown in **Fig. 14**. These materials are making an important contribution to high efficiency in large-scale generators.

6. Conclusion

This paper introduced the material development concepts and distinctive features of high performance non-oriented electrical steel sheets which are used as core materials for motors for automobiles, household appliances, industrial machinery, etc. In the future, with progress in the application of motors to automobiles and aircraft, it is considered that the applications of motors will become increasingly diverse and higher efficiency will be strongly demanded. JFE Steel will continue to develop new electrical steel sheets which respond to the diversifying needs of customers and will also propose motor application technologies, etc. which make it possible to demonstrate the properties of materials to the fullest possible extent.

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