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Recent Development of Non-Oriented Electrical Steel for HEV and EV in JFE Steel

OKUBO Tomoyuki*1 ODA Yoshihiko*2 SHIDARA Eitaro*3

Abstract:

In recent years, requirement in reducing CO_2 emissions has been increasing to prevent global warming. In the automotive sector, strict CO_2 emission regulations have been set in many countries and the electrification of powertrains is accelerating. JFE Steel has developed a variety of high-performance electrical steel sheets since 1954, when the company started manufacturing cold-rolled electrical steel sheets. In recent years, JFE Steel has also developed and manufactured electrical steel sheets for hybrid electric vehicles (HEVs) and electric vehicles (EVs). This paper introduces JFE Steel's electrical steel sheets for HEVs and EVs such as JNE™ for high-efficiency motors, JNP™ for high-torque motors, thin-gauge electrical steel JNEH™ for high-speed motors, and high-strength electrical steel JNT™ for rotors.

1. Introduction

Electrical steel (silicon steel) is a general term for Fe-Si alloys used as soft magnetic materials. The fact that addition of Si to Fe improves the soft magnetic properties of steel was discovered around 1900, and various technical improvements have been made in electrical steel since that time. Today, electrical steel is the most representative soft magnet material, and is widely used as the core material for motors and transformers. Electrical steels are broadly divided into two types, that is, grain-oriented and non-oriented electrical steels. As features of non-oriented electrical steels, which are the subject of this paper, this type is characterized by a comparatively random crystallographic orientation and small in-plane anisotropy of magnetic properties. For this reason, non-oriented electrical steel is mainly used as a core material for motors and other rotating machines.

Motors are devices that convert electrical energy to kinetic energy, and high conversion efficiency (motor efficiency) is demanded in that conversion process. Since consumption of electric power by motors accounts for approximately 60 % of power consumption in Japan[1)], improvement of motor efficiency can make a substantial contribution to energy conservation, not only in electrical equipment, but in the world as a whole. Because motor efficiency is largely influenced not only by the structure and design of the motor, but also by the properties of the electrical steel used as the core material, improvement of the properties of electrical steel has been required.

On the other hand, in recent years, there has also been increasing concern about energy-saving and reduction of CO_2 emissions from the viewpoint of preventing global warming. In particular, strict CO_2 emission regulations have been set for the automotive sector in many countries, and as countermeasure, the electrification of automobile powertrains is accelerating[2)]. In comparison with conventional gasoline-powered vehicles, in which the wheels are driven by only an internal combustion engine, broad reductions in CO_2 emissions can be expected with electric vehicles (EVs) and hybrid electric vehicles (HEVs) which use an electric motor or a hybrid system. However, particularly in the case of EVs, the large amount of expensive batteries which is necessary to extend the vehicle cruising range per charge is an issue. Thus, development and supply of electrical steel with even higher properties than in the past are demanded for the motors that are the heart of the EV powertrain.

JFE Steel began manufacturing non-oriented electrical steel sheets by cold rolling in 1954. From the 1990s into the 2000s, when HEVs first appeared and began to expand in the market, the company developed the electrical steel for high efficiency motors JNE™ and the thin-gauge electrical steel for high frequency use JNEH™, followed by the electrical steel for high-

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*1 Senior Researcher Deputy General Manager, Electrical Steel Research Dept., Steel Res. Lab., JFE Steel

*2 Dr. Eng., Principal Researcher, Steel Res. Lab., JFE Steel

*3 Manager, Electrical Steel Sec., Products Design & Quality Control for Sheet & Strip Dept., West Japan Works (Kurashiki), JFE Steel

torque motors JNP™ and the high-strength electrical steel for rotors JNT™ in the 2010s, when the shift to EVs began in earnest. JFE Steel has continuously supplied these materials to the market and is continuing to contribute to high efficiency in motors and the electrification of automobiles. This report describes JFE Steel's non-oriented electrical steels for HEVs and EVs.

2. Properties Required in HEV and EV Traction Motors

As described in the Introduction, high efficiency is strongly demanded in automotive traction motors, and strong requirements are also applied to downsizing and high torque from the viewpoints of weight reduction and space-saving. For this reason, the main type of motor used in automotive traction motors is the interior permanent magnet (IPM) motor. IPM motors are advantageous in terms of compact size and high torque because they can utilize magnet torque and reluctance torque. **Figure 1** is a schematic diagram showing the possible driving regions of traction motors in terms of torque and motor speed, and also notes the characteristics required in the motor and electrical steel in each region[3].

The first region is the high-torque, low-speed region, which corresponds to vehicle starting, acceleration and hill-climbing. Since high torque is necessary in this region, a large current is applied to the motor winding, and the core is magnetized to the high magnetic flux density region. Therefore, high magnetic flux density is required in the electrical steel material in order to obtain a high-torque motor with the most compact size possible.

The next regions are the low-torque, medium-speed region and the high-speed region, which correspond to city driving and expressway driving, respectively. Because a large part of the energy consumption in driving occurs in these region, improvement of the motor efficiency in these regions is an effective strategy for improving vehicle fuel consumption and electricity consumption. Due to the high motor speed (revolutions per minute) in this region, the percentage of iron loss in motor loss is large in these regions, which means that low iron loss under high-frequency magnetization is required in the electrical steel. In addition, since permanent magnets are embedded in the rotor in IPM motors, high stress concentrations are generated under high-speed rotation in the parts (bridges) where the magnets are held. To prevent destruction of the rotor and scattering of the magnets in high-speed rotation, high strength and high fatigue strength are required in the electrical steel.

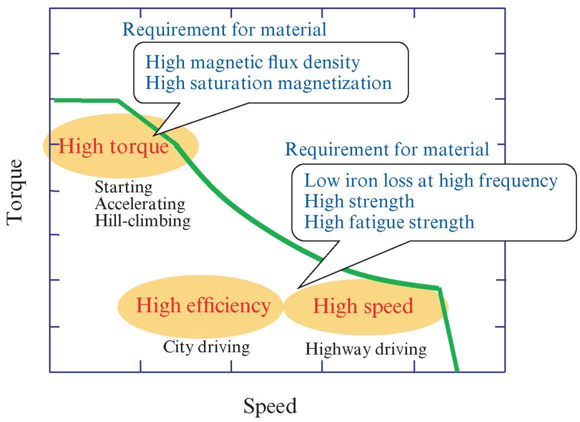

Fig. 1 Demands for HEV and EV traction motors and electrical steel sheets

As outlined above, low iron loss, high magnetic flux density and high strength are required in the electrical steel for HEVs and EVs, but since these are mutually-contradictory, satisfying these requirements simultaneously is a challenge. Accordingly, since it would be difficult to satisfy all of these properties with one type of electrical steel, various types of electrical steels are used as appropriate for the structure and design of the motor.

The next chapter introduces the electrical steel for high efficiency motors JNE, which has an excellent balance of iron loss and magnetic flux density, the electrical steel for high-torque motors JNP, which features high magnetic flux density, the thin-gauge electrical steel for high-frequency use with low high-frequency iron loss JNEH, and the high-strength electrical steel for use in rotors JNT.

3. Non-Oriented Electrical Steels in JFE Steel

3.1 Electrical Steel for High Efficiency Motors "JNE™"

Low iron loss and high magnetic flux density are required in electrical steel for HEV and EV traction motors. Since increasing Si addition is effective for reducing the iron loss of electrical steel from the viewpoint of reducing eddy current loss by increasing specific resistance, approximately 3 mass% of Si is added to high-grade electrical steels. On the other hand, Si is a nonmagnetic element, which means magnetic flux density and saturation magnetization decrease as the Si content increases. Therefore, it is difficult to manufacture materials that satisfy both low iron loss and high magnetic flux density by the technique of increasing Si addition.

Texture control may be mentioned as a technique for achieving high magnetic flux density without adversely affecting iron loss. This is a technique whereby magnetic properties are improved by controlling the crystal orientation (texture) of the crystal grains that comprise an electrical steel sheet. Among the crystal orientations of Fe, it is difficult to magnetize the <111> axis, which is called the hard axis of magnetization, whereas the <100> axis, which is called the easy axis of magnetization, has the property of being extremely easy to be magnetized. Accordingly, the magnetic flux density of electrical steel can be increased by increasing the proportion of crystal grains having the <100> orientation in the plane of the steel sheet. In the JNE series, texture is improved in comparison with the conventional material by control of trace components and optimization of the manufacturing conditions, and in addition, impurity elements are reduced and the alloy design of Si, Al, *etc*. is optimized [4–6].

Figure 2 shows a comparison of the magnetic flux density and iron loss of the JNE series (sheet thickness: 0.35 mm) and the conventional JN series. In comparison with the conventional material, the JNE series has an excellent balance between iron loss and magnetic flux density, and also has a higher magnetic flux density than the conventional material with the same iron loss. **Figure 3** shows the hardness of the JNE series. The JNE series also has a lower hardness alloy design in comparison with the conventional material at the same iron loss, so JNE materials have the merit of suppressing press die wear in the punching process in motor production. Thus, because the JNE series improves motor efficiency by realizing low iron loss, makes it possible to downsize motors owing to its high magnetic flux density, and achieves long press die life as a result of its low hardness alloy design, JNE materials are widely used in commercial HEV traction motors, *etc*.

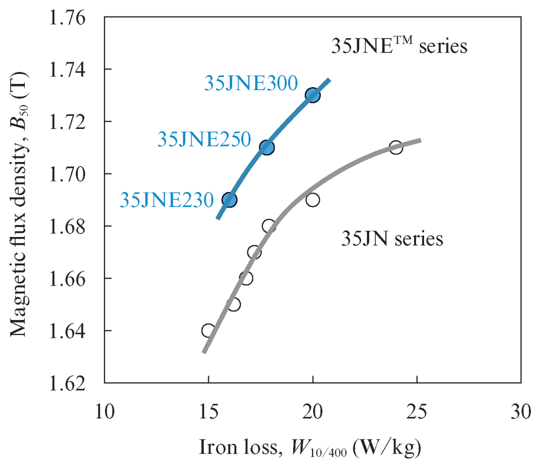

Fig. 2 Magnetic properties of JNE™ series

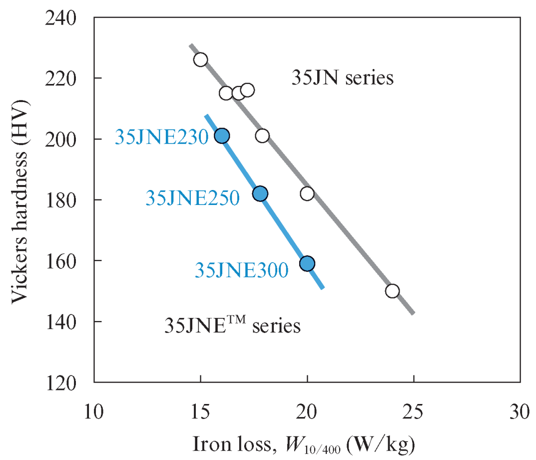

Fig. 3 Vickers hardness of JNE™ series

3.2 Electrical Steel for High-Torque Motors "JNP™"

Large torque is required in HEV and EV traction motors during starting, hill-climbing and acceleration. While increasing the dimensions of the motor is effective for obtaining large torque, it is desirable that the motor should be as compact as possible from the viewpoints of space restrictions and weight reduction. Thus, a further increase in magnetic flux density is required in electrical steels used as core materials. Based on this requirement, the JNP series was developed by applying technologies for optimization of the alloy design of Si, Al, Mn and other elements, reduction and mitigation of the effects of impurities, and texture improvement by use of grain boundary segregation elements and optimization of intermediate processes.

The magnetic properties of the JNP series (sheet thickness: 0.35 mm) are shown in **Fig. 4**. In comparison with the JNE series, at the same iron loss, magnetic flux density is increased further in the JNP series. **Figure 5** shows a comparison of the textures (φ_2 = 45° cross section ODF) [7] of 35JNP7 and 35JNE230, which are materials with similar iron loss. It can be said that 35JNP7 has an excellent texture, as the intensities of

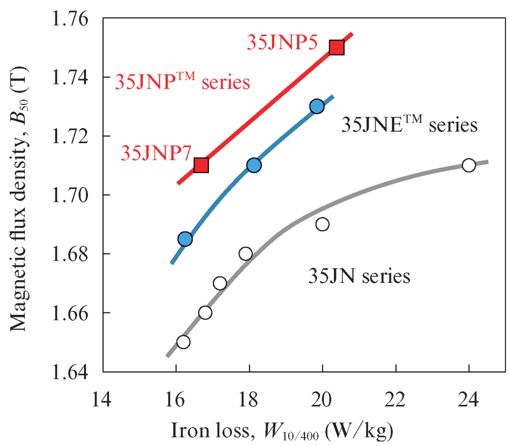

Fig. 4 Magnetic properties of JNP™ series

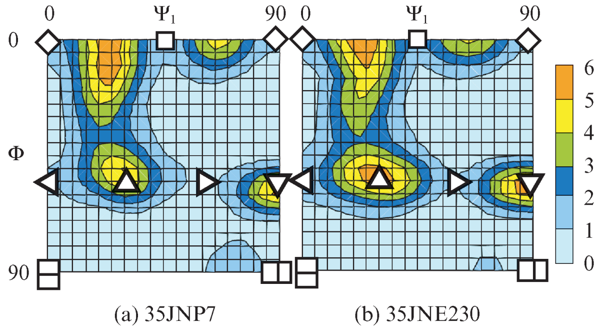

Fig. 5 Comparison of texture between JNP™ and JNE™

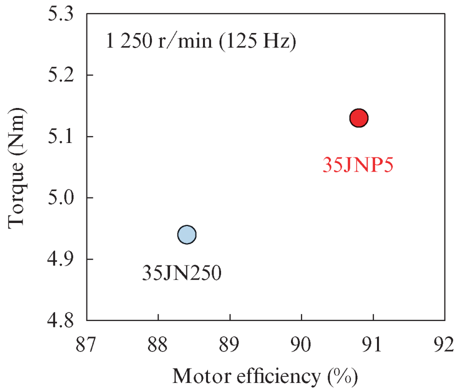

Fig. 6 Motor properties of 35JNP5 used for the direct drive motor

{111}<112>, which adversely affect magnetic properties, are lower in this material. Due to its high magnetic flux density, the JNP series is suitable for motors in which particularly high torque is required, and has already been adopted in commercial HEV motors.

One type of EV motor in which high torque is required is the direct-drive in-wheel motor. Because this type of motor is housed in the wheel, it has the advantage of increasing the degree of freedom in auto body design, in that a larger vehicle interior space can be used. From this viewpoint, this is considered to be a promising drive system, especially for compact cars. High torque is required in these motors because they must rotate the tires directly without intervening gears. Moreover, in comparison with systems in which the motor is rotated at high speed by using gears, the direct-drive type has the feature of a low ratio of iron loss in motor loss due to its lower motor speed. Based on this fact, high magnetic flux density is a more important requirement than low iron loss in electrical steels for use in direct-drive motors.

To confirm the superiority of the developed material in direct-drive motors, an IPM type in-wheel motor with an output of 1.6 kW was fabricated, and its motor characteristics were evaluated. **Figure 6** shows the motor efficiency and torque at a motor speed of 1 250 r/min (equivalent to a vehicle speed of 60 km/h)[7]. In comparison with the 35JN250 used as a comparison material, 35JNP5 improved both motor efficiency and torque, and thus can be considered a suitable core material for direct-drive motors.

Induction motors may also be mentioned as another type of motor that requires high magnetic flux density. Induction motors are highly versatile motors with a 90 % share of the total number of motors produced in Japan[8]. However, because they are rare-earth-free motors that do not use rare earth magnets, they have also been adopted as the main motors of EVs in an increasing number of cases from the viewpoints of cost reduction and reduction of procurement risk.

Motor loss can be broadly divided into copper loss, iron loss and mechanical loss. Because induction magnets utilize a magnetic field created by the induction current generated by the secondary conductor of the rotor, and do not use magnets, the ratio of copper loss is high in comparison with permanent magnet motors[9]. This suggests that a stronger copper loss reduction effect and motor efficiency improvement effect can be achieved in induction motors by increasing the magnetic flux density of the core material. Since the magnetic flux density of the JNP series is greatly improved in comparison with the JN series and JNE series, an efficiency improvement effect can be expected by applying JNP series in induction motors. In a study using a small-scale model motor (3-phase, 6-pole induction motor), it was reported that application of the JNP series had an efficiency improvement effect in the region where the operating magnetic flux density is higher than 1.6 T[10]. This is considered to be due to the fact that the copper loss ratio increases at higher operating flux densities, and shows that high efficiency can be achieved in induction motors by applying the JNP series.

3.3 Thin-Gauge Electrical Steel for High-Frequency Use "JNEH™"

Because motor output is determined by the product of torque and rotating speed, decreased torque due to motor downsizing is compensated for by increasing motor speed. There are strong needs for compact, lightweight traction motors for EVs and HEVs, and downsizing and high output density are progressing by increasing the maximum rotating speed of the motors[11]. Accompanying this trend, use of higher-frequency excitation frequencies in the electrical steels used as core materials is also progressing. The iron loss of electrical steel consists of hysteresis loss and eddy current loss, but among these, hysteresis loss is proportional to frequency, while eddy current loss W_e is proportional to the square of frequency, as shown by the following equation.

$$W_e = (\pi B_m f t)^2 / 6\rho \quad \cdots\cdots (1)$$

where, B_m: excitation magnetic flux density, f: frequency, t: sheet thickness, ρ: resistivity. Since this equation means the ratio of eddy current loss increases rapidly as the motor speed increases, suppressing the eddy current loss generated in electrical steel is a major issue for achieving higher efficiency in traction motors.

Two methods of reducing eddy current loss are conceivable: decreasing the sheet thickness and increasing resistivity. Because Eq. (1) showed that eddy current loss is proportional to the square of sheet thickness, eddy current loss can be reduced effectively by decreasing sheet thickness. While increasing resistivity by Si addition has the problem of reducing saturation magnetization, decreasing the sheet thickness has the advantage of reducing eddy current loss without affecting saturation magnetization. The development of electrical steels for high frequency applications is progressing against this backdrop[12].

The magnetic properties of the thin-gauge electrical steel sheets 30JNE1500, 25JNE1350 and 20JNEH1200 with thicknesses of 0.3 mm, 0.25 mm and 0.2 mm, respectively, are shown in **Fig. 7** and **Table 1**. In comparison with the highest-grade class material with a thickness of 0.35 mm, these results show that high frequency iron loss can be reduced by approximately 20 to 40 % by applying the thin-gauge electrical steels. These thin-gauge electrical steels are effective for improving the efficiency of traction motors with high rotational speeds, and have already been adopted in numerous cases.

To verify the motor efficiency improvement effect of applying thin-gauge electrical steel, the test IPM motors shown in **Table 2** were fabricated, and their motor efficiency was evaluated. In this study, the cores were prepared by wire cutting and impregnation bonding to eliminate the effects of residual strain induced by machining. In the evaluation, the rotor material was fixed as 25JNE1350, and only the stator material was changed to 25JNE1350 or 35JNE300. **Figure 8** shows the obtained motor efficiency maps. Motor efficiency in the high-speed rotation region was particularly improved by application of thin-gauge electrical steel.

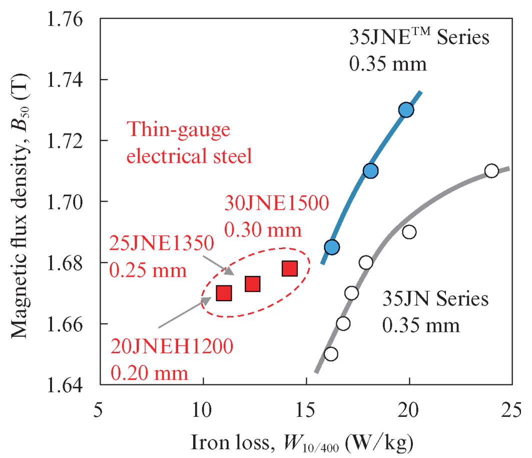

Fig. 7 Magnetic properties of thin-gauge electrical steel sheets

Table 1 Comparison of magnetic properties between thin-gauge electrical steel sheets and 35JN230

Grade	Thickness (mm)	$W_{15/50}$ (W/kg)	$W_{10/400}$ (W/kg)	B_{50} (T)
35JN230	0.35	2.10	17.2	1.66
30JNE1500	0.30	2.10	14.2	1.68
25JNE1350	0.25	2.05	12.4	1.67
20JNEH1200	0.20	2.13	11.0	1.67

Table 2 Specifications of the test motors

Items	Specification
Rated power output	9 kW
Input voltage	400 V_{DC}
Current limit	45 Arms
Current phase angle	0.0—65.0 deg
Number of poles / slots	8/48
Outer diameter of stator	171.2 mm
Stacking length	14 mm
Winding connection	Three phase connection, distributed

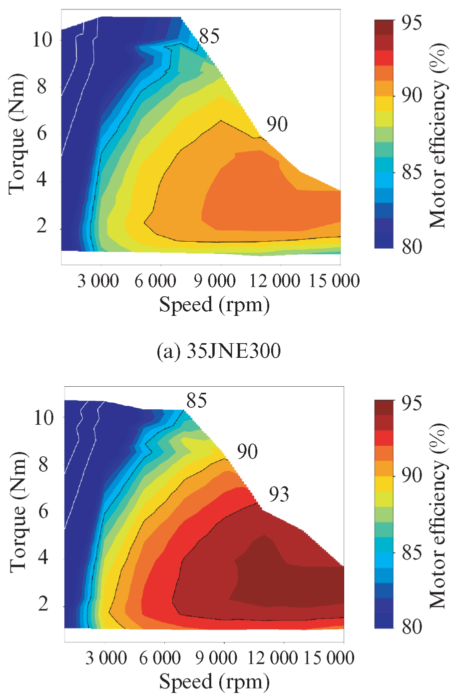

Fig. 8 Comparison of motor efficiency maps

This improvement is due to a decrease in the high-frequency iron loss of the core material, indicating that application of thin-gauge electrical steel is extremely effective for achieving high efficiency in HEV and EV traction motors.

Although traction motors for HEVs and EVs are generally driven by PWM control using an inverter, it is known that the harmonics included in the voltage waveform increase iron loss. Thin-gauge electrical steels are also effective for suppressing increased iron loss caused by inverter excitation, as they have the feature of low iron loss even under nonsinusoidal excitation[13]. In addition, thin-gauge electrical steels have the advantage of a smaller increase in iron loss, as they are relatively unaffected by strain due to press working in the motor manufacturing process[14]. From this viewpoint as well, thin-gauge electrical steel is a suitable material for achieving high efficiency in motors.

3.4 High-Strength Electrical Steel for Rotors "JNT™"

A schematic diagram of an IPM motor is shown in **Fig. 9**. IPM motors have a structure in which magnets are embedded in the slot parts inside the motor. During high-speed rotation, large stress is applied to the parts (bridge parts) that hold the magnets. Although increasing the width of the bridge to reduce stress is effective for preventing bridge fracture, this increases the leakage flux that flows through the bridges and is a problem in terms of reduced torque and reduced efficiency. Therefore, sufficient yield strength so that plastic deformation will not occur at stress concentrations during high-speed rotation and fatigue strength to avoid fatigue fracture due to cyclical stress are necessary in electrical steels which are to be used as core materials[15]. Because iron loss occurs at the rotor surface due to the harmonics, reduction of high-frequency iron loss is also required to improve motor efficiency and suppress demagnetization of the magnets.

With this background, JFE Steel developed the high-strength electrical steel 35JNT590TK for rotors shown in **Fig. 10** and **Table 3**[16]. In this material, in addition to solute strengthening by Si, *etc.*, grain refinement strengthening was also applied, achieving an increase in yield strength of about 40 % in comparison with the conventional material. Applying this high-strength electrical steel as a rotor material can contribute to downsizing by increasing the maximum motor speed, and to improvements in torque and motor efficiency by narrowing the bridge parts. It should be noted that application only to rotors is recommended because the iron loss of this electrical steel is higher than that of the conventional material due to grain refinement. On the other hand, even though rotor iron loss increases, the effect is slight because the iron loss that occurs in the rotor is small compared with the total iron loss of permanent magnet motors.

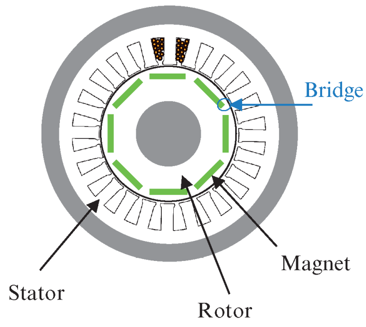

Fig. 9 Schematic diagram of interior permanent magnet (IPM) motor

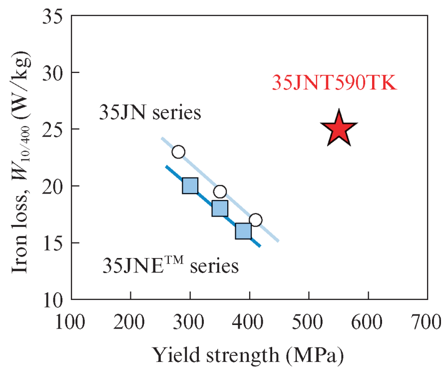

Fig. 10 Magnetic and mechanical properties of high-strength electrical steel sheets

Table 3 Comparison of magnetic and mechanical properties between high-strength electrical steel sheet and 35JN230

Grade	$W_{10/400}$ (W/kg)	B_{50} (T)	YS (MPa)	TS (MPa)	HV
35JN230	17.2	1.66	401	527	215
35JNT590TK	24.0	1.66	550	620	223

4. Conclusion

This paper introduced the technical concepts, features and material properties of the high-performance non-oriented electrical steels used as core materials of HEV and EV traction motors. By continuously supplying these developed steels to the market, JFE Steel has been continuing to contribute to high efficiency in motors and the electrification of automobiles. In the future, it is thought that the wave of electrification will expand to include not only automobiles, but also aircraft, ships and other forms of mobility, resulting in further diversification of the needs for motors and electrical steels. Based on the Corporate Vision of the JFE

Group, "Contributing to society with the world's most innovative technology," JFE Steel will also continue technical development to enable production and stable supply of high-performance electrical steels in the future so as to contribute to global electrification and energy conservation.

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