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Electrical Steels for Advanced Automobiles —Core Materials for Motors, Generators, and High-Frequency Reactors—†

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Abstract:

To develop electrical steels suitable for the rapidly-progressing electrification of automobiles and establish the optimum use technologies, the properties of core materials in actual machines were investigated using methods including model motor measurement, local magnetic measurement in model motors, and model transformer measurement. Based on the knowledge obtained as a result of model motor measurements, "JNE," featuring high flux density and low iron loss, and "JNEH," with low high frequency iron loss, were developed as non-oriented electrical steels for automotive applications. "JGE" was developed as a grain-oriented electrical steel suitable for segmented-type motor cores and features lower iron loss in directions off the rolling direction than conventional grain-oriented electrical steel. Products developed for high frequency reactor applications include "JFE Super Core JNEX," which realizes low noise and low iron loss in the 400 Hz–10 kHz region by addition of 6.5% Si, and "JFE Super Core JNHF," which reduces iron loss in the very high frequency region from 5 kHz to 100 kHz by a gradient distribution of Si in the sheet thickness direction.

1. Introduction

In the past, electric energy-using devices in automobiles were generally limited electrical components such as the alternator, ignition system, starter, headlights, instruments, and small motors such as wiper motors. Recently, however, motors have been used with increasing frequency in all parts of the automobile in pursuit of safety and comfort and from the viewpoint of improved fuel economy, and electronic fuel injection, electric power steering systems, electric automotive air conditioners, and other equipment have now reached the practical stage. From the viewpoint of reducing CO_2 emissions/improving fuel economy, automobiles which utilize electrical energy as drive power, such as the electric vehicle (EV), hybrid electric vehicle (HEV), and fuel cell vehicle (FCV), are also progressing rapidly. Moreover, electromagnetic valves and various types of by-wire technologies are in the development process. Thus, electric energy is expected to account for an increasingly large percentage of energy consumption in automobiles.

In motors, generators, and reactors, which are the main parts of electric energy-using equipment in automobiles, an iron core (magnetic core) is necessary to temporarily convert electric energy to magnetic energy during electric-mechanical energy conversion and power conversion. Considering the high use frequency of electrical steels, it can be said that these are the most important magnetic materials used as materials for iron cores of this type. Low iron loss/high performance in electrical steels is an essential task for responding to the heightened trend toward global environmental protection in recent years and the needs of advanced automobiles. Therefore, JFE Steel is evaluating properties in actual machines, bearing in mind the needs of automo-

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tive applications, and carrying out material development based on the results.

This paper introduces actual machine property evaluation technologies for clarifying the various properties desired in electrical steel for use as core materials in automobiles and describes electrical steel products developed by JFE Steel for automotive applications.

2. Evaluation Technologies

2.1 Model Motor Evaluation

To clarify the property requirements for electrical steel in actual motors, the correspondence relationship between material magnetic properties and properties in actual machines was investigated using model motors.[1,2] The types of motors investigated here were the brushless DC (BLDC) motor, which is frequently used as an EV drive motor and electric power steering system motor in Japan, and the induction motor, which has been studied in many cases as a electric vehicle drive motor in the United States and Europe. The tested BLDC motor was an 8-pole, 12-slot surface permanent magnet (rare-earth magnet) motor with a driving voltage of 48 V and rated capacity of 300 W; the induction motor was a 3-phase, 6-pole, 36-slot motor with a driving voltage of 120 V and rated capacity of 400 W. As samples for measurement, in this study, stators manufactured from various grades of electrical steel were prepared, and stress-relief annealing was performed after punching/interlocking. Measurements were performed while gradually increasing torque from a no-load rotation condition at the above-mentioned driving voltages, and the point of maximum efficiency was obtained. With this BLDC motor, the rotational speed at maximum efficiency was approximately 1 500 rpm, against a no-load rotational speed of 2 100 rpm. With the induction motor, the rotational speed at maximum efficiency was approximately 2 300 rpm, against a no-load rotational speed of 2 400 rpm. The fundamental frequencies of the tested BLDC motor and induction motor at the rotational speed at maximum efficiency are 100 Hz and 120 Hz, respectively.

Figure 1 shows the effect of material iron loss on the maximum efficiency of the BLDC motor and induction motor. With the BLDC motor, iron loss at 400 Hz, $W_{10/400}$ shows a better correlation with maximum efficiency than does $W_{15/50}$, although the latter has generally been used as the iron loss property of electrical steel.[1] This finding indicated that, in BLDC motors, iron loss at frequencies higher than the fundamental frequency is important for improving motor efficiency. The cause of this is expected to be the effect of higher harmonics on the flux density waveform.[1]

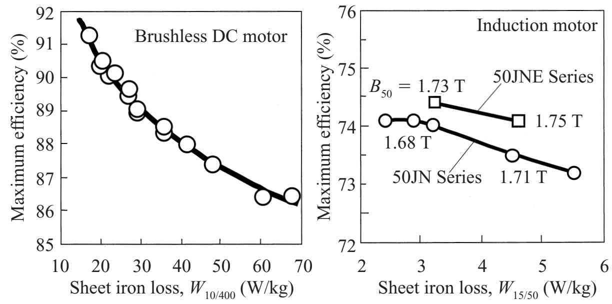

Fig. 1 Dependence of maximum efficiency on sheet iron loss

With the induction motor, both material iron loss, $W_{15/50}$ and flux density, B_{50} affect maximum efficiency. Although motor efficiency is improved by using low iron loss electrical steel, improvement of B_{50} has an effect similar to improvement of iron loss, showing that core materials which pursue only low iron loss are not necessarily suitable for induction motors. In explaining these differences in the BLDC motor and induction motor, although iron loss accounts for much of the loss in BLDC motors, copper loss accounts for a large percentage in induction motors, and improvement in B_{50} suppresses the exciting current value, thereby reducing copper loss.[2]

Figure 2 shows the effect of output on the efficiency of the BLDC motor. **Table 1** shows the magnetic properties of the materials used in the stators after stress-relief annealing. Although maximum efficiency increases in materials with reduced iron loss, materials with a high magnetic flux density, B_{50} show higher motor efficiency

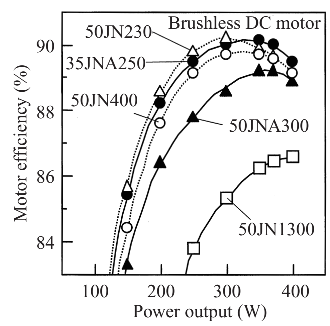

Fig. 2 Dependence of motor efficiency on power output

Table 1 Magnetic properties of stator core materials used

	$W_{15/50}$(W/kg)	B_{50}(T)
35JNA250	2.36	1.72
50JNA300	2.63	1.72
50JN230	2.16	1.67
50JN400	2.86	1.71
50JN1300	5.16	1.77

Test made on 25 cm Epstein sample (L + C) after stress-relief annealing at 750°C for 2 h in N_2

in the high output region. A similar tendency was also confirmed with the induction motor.

The above results revealed that the contribution of iron loss to the efficiency of BLDC motors is large, and reduction of iron loss in the frequency region higher than the fundamental frequency (in the above results, approximately 4 times higher) is effective. On the other hand, with induction motors, it was ascertained that improvement of magnetic flux density, B_{50}, together with reduction of iron loss at around the fundamental frequency, makes a large contribution to higher efficiency. It was also found that high flux density material is advantageous for improving efficiency in the high output region. Because high efficiency under various driving conditions is required in drive motors for EV and HEV, it is important to select core materials in consideration of the output region in which the motor will be used.

2.2 Local Magnetic Measurement in Model Motors

To clarify the distribution of local magnetic properties in the interior of motor cores and obtain guidelines for the optimum core configuration and material selection, a technique for measuring the local magnetic properties inside the stator core was developed and used in measurements of a BLDC motor and induction motor. **Figure 3** shows a schematic diagram of the local magnetic measurement using the needle probe method and Hall probes. In this method, magnetic values in uppermost layer of the stator are measured.

The BLDC motor was the same type as the motor described in the previous section. A JFE Steel product, "35JNE300," was used as the core material. As the induction motor, a single-phase, 2-pole, 24-slot motor with a driving voltage of 100 V and frequency of 60 Hz was used. In this case, the core material was JFE Steel's "50JN400." With both motors, the measurements were performed with the winding in a raised condition in order to insert the probes into the tooth area.

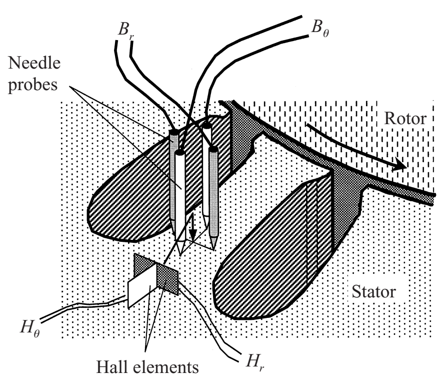

Fig. 3 Schematic view of local magnetic measurement in a stator core

Figure 4 shows the local flux density and magnetic field distributions in the BLDC motor in the radial direction and circumferential direction.[3)] The maximum values of the radial and circumferential direction components of flux density and the magnetic field at a local point are indicated by B_{rm}, $B_{\theta m}$, H_{rm}, and $H_{\theta m}$, respectively. It can be understood that the flux density in the radial direction is high in the teeth and around the base of the teeth (joint with yoke), whereas the flux density in the circumferential direction is large in the yoke and the tips of the teeth. This distribution agrees with the results obtained from calculations by magnetic field analysis. However, the non-uniform flux density distribution observed inside the yoke was a result which could not be predicted by magnetic field analysis.

The magnetic field in the circumferential direction was high at the tips of the teeth, and in particular, showed a high value at the side which had previously met the rotating rotor. This point is also noteworthy as a distribution different from the results with magnetic field analysis.

The foregoing measured results suggest the possibility that the increase in iron loss due to rotational iron loss and non-uniformity of magnetic flux is greater than that predicted from calculations by magnetic field analysis.

Figure 5 shows the distributions of local flux density and the local magnetic field in the induction motor; **Fig. 6** shows the distribution of local iron loss. The radial component of flux density is highest in the teeth, and high flux density areas are also distributed around the base of the teeth on the inner side of the yoke. The radial component of the magnetic field is particularly high at the tips of the teeth. Local iron loss reflects the distribution of flux density and the magnetic field in the radial direction, being high in the teeth and the inner

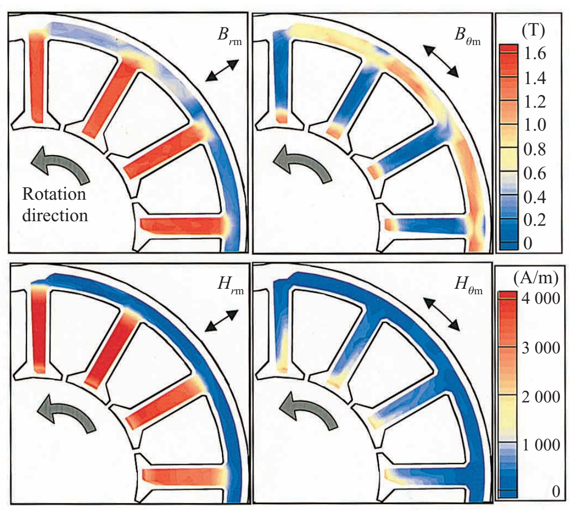

Fig. 4 Distribution of local magnetic property in stator core of brushless DC motor

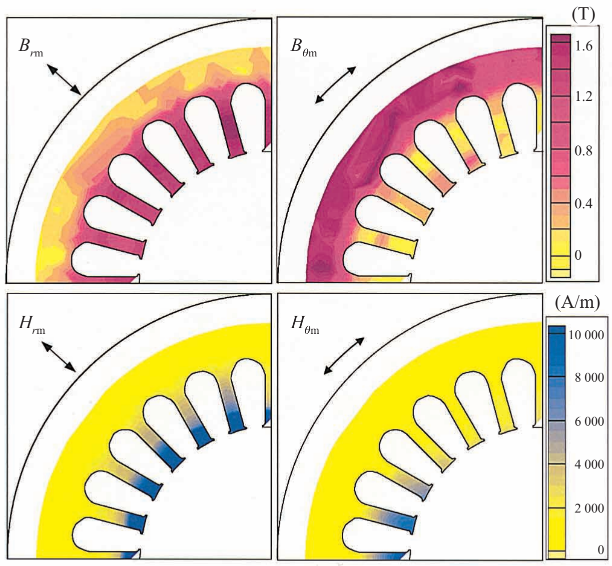

Fig. 5 Distribution of local magnetic propery in stator core of induction motor

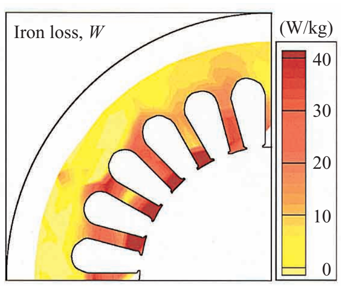

Fig. 6 Distribution of local iron loss in stator core of induction motor

side of the yoke, and in particular, large iron loss occurs at the tips of the teeth.[4,5]

The above results revealed that flux density and iron loss are highest in the teeth in both the BLDC motor and the induction motor, and flux density/iron loss is also moderately high in the vicinity of the tooth base. Based on these results, it is expected to be possible to improve motor efficiency/performance by material selection and motor design which attach importance to the magnetic properties of the teeth.

In the future, improvement in the accuracy of predictions of motor characteristics is expected to be possible by comparing the results of local magnetic measurements by this method and calculations by magnetic field analysis and clarifying the causes of differences between the two.

3. Electrical Steels Suitable for Motor/Generator Cores

3.1 High Efficiency Electrical Steels

Based on the experimental results with the model motors described in the previous chapter, it can be said that reduction of iron loss in the frequency range corresponding to the motor type and improvement of magnetic flux density, B_{50} are important in automotive motors in which high efficiency is required over a wide range of outputs. From this viewpoint, JFE Steel has developed the “JNE Series,” “JNP Series,” and “JNA Series” as product groups which realizes high magnetic flux density, B_{50} while maintaining iron loss equivalent to that of the conventional JIS grade product groups. As thin products which give priority to low iron loss in the high frequency region, JFE Steel also developed the “JNEH Series.” **Figure 7** shows the relationship between iron loss ($W_{15/50}$ and $W_{10/400}$) and B_{50} in these products. Outlines of the respective products are presented below.

(1) JNE Series

Material in which low iron loss/high magnetic flux density is achieved by control of inclusions and texture. The highest grade product, 35JNE230, achieves $W_{15/50} \leqq 2.3$ W/kg and $B_{50} \geqq 1.67$ T, while hardness, which deteriorates punchability, is HV $\leqq$ 200.

(2) JNP Series

Product group with the highest B_{50} in JFE Steel’s product line. In the JNP Series, 50JNP1 achieves $B_{50} \geqq 1.77$ T in combination with $W_{15/50} \leqq 8.0$ W/kg.

(3) JNA Series

While securing high flux density, B_{50}, this material also pursues iron loss reduction after stress-relief

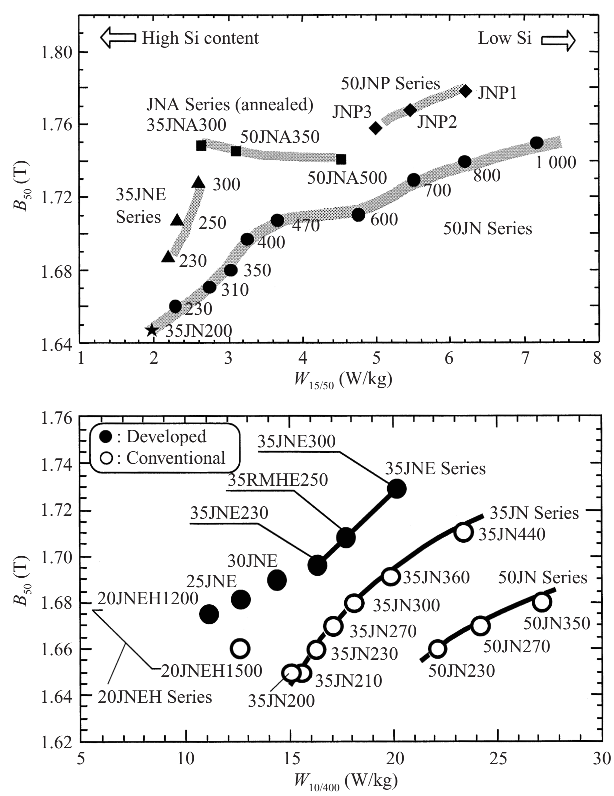

Fig. 7 Maps of electrical steel products of JFE Steel

annealing by the customer, using improvement of grain growth by control of inclusion particles as the main technology. A full line of products is available, from 50JNA600 ($W_{15/50} \leqq 6.0$ W/kg) to 35JNA300 ($W_{15/50} \leqq 3.0$ W/kg).

(4) JNEH Series

Materials with excellent iron loss in the high frequency region. The highest grade product, 20JNEH1200, achieves $W_{10/400} \leqq 12.0$ W/kg. Suitable as a motor material for automotive applications in which importance is attached to efficiency at high rotational speeds.

3.2 Grain-oriented Electrical Steel for Segmented Cores, "JGE"

The results of local magnetic property measurements in model motors described in the previous chapter revealed that both BLDC motors and induction motors display high magnetic flux density/iron loss in the tooth part. Therefore, the method of applying materials with high permeability in one direction, such as grain-oriented electrical steel (GO), as a segmented core in the stator is considered effective for high torque/high efficiency. However, because it is impossible to avoid magnetic flux components off the rolling direction in many segmented core structures,[6,7] iron loss may increase in the vicinity of the tooth base, making it impossible to obtain the desired properties. Furthermore, because ordinary GO has a ceramic coating on the surface, when cores are manufactured by punching, die wear increases markedly and high productivity cannot be achieved. To solve this problem, JFE Steel developed a GO, "JGE," which possesses satisfactory iron loss characteristics in the transversal direction and improves punchability.[8] **Figure 8** shows the dependence of iron loss characteristics on the cutting angle relative to the rolling direction in JGE and a conventional grain-oriented electrical steel (CGO). Although the iron loss of JGE in the rolling direction is somewhat inferior to that of CGO, the iron loss values when the cutting angle deviates from the rolling direction are considerably reduced in comparison with CGO. Considering this, it can be said that JGE is a suitable material for segmented type cores when the rolling direction is used as the tooth direction. **Figure 9** shows a comparison of punchability with CGO. In comparison with CGO, the increase in burr height is reduced with JGE, showing the same level as non-oriented electrical steel with the same Si content.

Figure 10 shows the results of a comparison of efficiency using model motors (BLDC motors) manufactured from non-oriented electrical steel and JGE. The motor using JGE displayed high efficiency, particularly in the high output region, confirming the effectiveness of applying JGE as a segmented core.

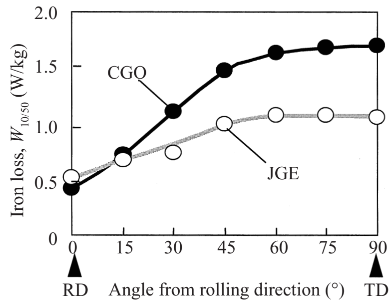

Fig. 8 Dependence of iron loss on angle from rolling direction

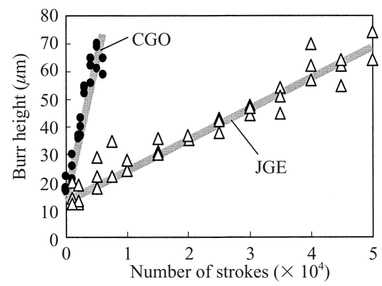

Fig. 9 Change in burr height with number of punching

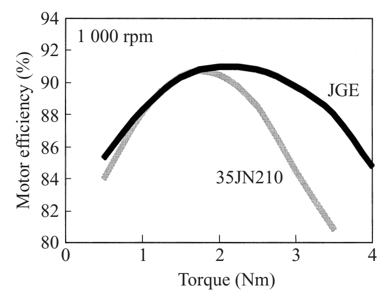

Fig. 10 Dependence of motor efficiency on torque

4. Electrical Steels Suitable for Reactors and Ignition Coils

4.1 JFE Super Core "JNEX" and "JNHF"

Hybrid electric vehicles (HEV) and fuel cell vehicles (FCV) are equipped with a converter/inverter for power conversion. The properties of low iron loss in the high frequency region for compactness and weight reduction, together with low noise for quietness are required in the core materials used in this application. From this viewpoint, JFE Super Core based on a 6.5% Si alloy is the optimum material, and can greatly improve product performance when used in reactors for boost converters, filter circuits of converter/inverters, current sensors, and similar parts.

(1) JNEX

JNEX is a non-oriented electrical steel with a 6.5 mass% content of Si. Fe-Si alloys show their maximum permeability at an Si content of 6.5% and magnetostriction is virtually zero. Magnetostriction

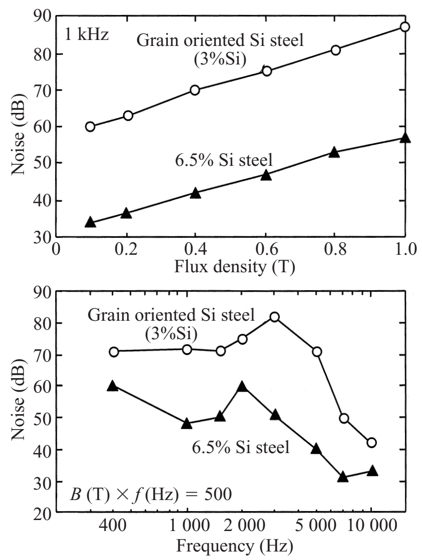

Fig. 11 Noise of model transformer

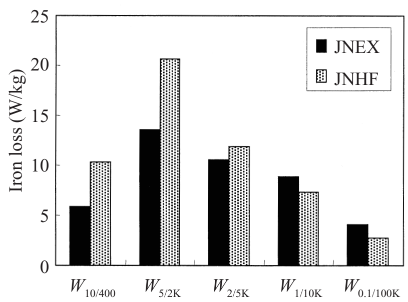

Fig. 12 Iron losses of JNEX and JNHF

vibration of the core is reduced by this extremely low magnetostriction, realizing low noise. **Figure 11** shows the noise measured in a single-phase stacked-type model transformer.[9] It can be understood that generated noise is extremely low in comparison with the GO which is generally used as a transformer material. Because of zero magnetostriction, deterioration in magnetic properties due to stress can be suppressed by using JNEX, and it is possible to prevent property changes due to the stress which occurs when reactor cores are treated by resin molding for insulation protection. Moreover, due to the high specific resistance of the material, low iron loss is achieved in the high frequency range of approximately 400 Hz to 10 kHz. Therefore, it is possible to realize low iron loss in reactors which are subjected to superposed high frequencies by PWM (pulse width modulation) control, etc.[10]

In motor core applications, JNEX with low iron loss in the high frequency region is also suitable for multi-pole designs, high rotational speeds, and high frequency superposition, and is used as a core for micro gas turbines. The possibility of improving motor efficiency by applying JNEX in cores for switched reluctance motor (SRM), which is expected to be used as a next-generation motor, has also been confirmed.[11]

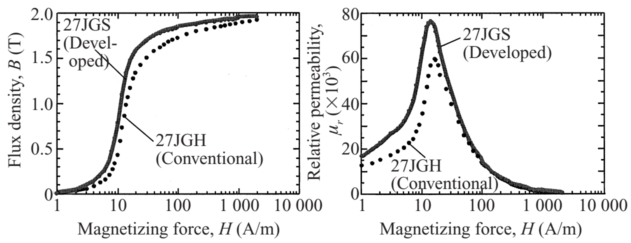

Fig. 13 Magnetization and permeability curves of 27JGS and 27JGH

(2) JNHF

JNHF is a gradient-type high Si steel sheet in which the Si content is 6.5% only at the sheet surface and is reduced in the sheet thickness direction,[12] and displays lower iron loss than JNEX in the high frequency region above 10 kHz, as shown in **Fig. 12**. It also offers superior punchabilty in comparison with JNEX due to the gradient distribution of the Si content.

4.2 Grain-oriented Electrical Steel for Direct Ignition Coils

The ignition coil is a type of transformer which produces the high voltage necessary for ignition in the engine combustion chamber, generating the secondary voltage necessary for discharge of the ignition plug when the primary current is shut off. The features required to obtain this high secondary voltage are high core magnetic energy generated by the primary current, combined with high response when the primary current is shut off a GO with high magnetic flux density and excellent permeability characteristics are needed for this requirements. High magnetic flux density also makes it possible to reduce the size of the core, contributing directly to miniaturization of stick-type ignitions.

JFE Steel developed a GO, "JGS," which displays higher magnetic flux density than conventional GO and has won an excellent reputation as a transformer core material.[13] As a representative example, **Fig. 13** shows the magnetization and permeability curves of JGS in the 27P100 class in comparison with the conventional JGH. B_8 of JGS is higher than that of JGH by 0.04 T, and permeability in low magnetic fields is also excellent. Application of JGS in core materials for direct ignitions is expected to make a significant contribution to miniaturization.

5. Conclusion

This paper has introduced technologies for evaluating the properties of electrical steels in actual applications at JFE Steel and described electrical steel product groups suitable for automotive applications based on the results.

Measurements using model motors revealed that, in BLDC motors, reduction of iron loss in electrical steel in the frequency region higher than the fundamental frequency functions advantageously in improving motor efficiency, while in induction motors, the magnetic flux density, B_{50} of the electrical steel has an effect on motor efficiency similar to that of iron loss. In both types of motors, electrical steels with high magnetic flux density, B_{50} are more advantageous for high efficiency in the high output region. Local magnetic measurements of model motors also revealed that magnetic flux density and iron loss are large in the tooth part and in the area of the tooth/yoke joint.

Based on the above-mentioned results, the lineup of electrical steels suitable for automotive applications includes high magnetic flux density electrical steel, electrical steel for high frequency use, and grain-oriented electrical steel (GO) for segmented cores, “JGE.” This paper has also introduced a high Si electrical steel, “JFE Super Core,” as an electrical steel for reactor applications, and a high flux density GO, “JGS,” as an electrical steel which is suitable for direct ignition coil applications.

As the pursuit of comfort and response to global environmental problems in automobiles are expected to become increasingly important, electric energy will be used with increasing frequency as a primary means of solving these problems. Because the role which electrical steel should play in these trends is a large one, further improvements in properties and performance, considering actual applications, are expected.

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