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Recent Progress of High-Silicon Electrical Steel Sheets in JFE Steel

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Abstract:

In recent years, iron loss reduction at high frequencies has been strongly required for core materials to increase efficiency and downsize electrical equipment. JFE Steel developed the continuous siliconizing process using chemical vapor deposition (CVD) and started manufacturing 6.5% Si steel sheet JNEX™ in 1993, and also developed a new technology to control the Si concentration distribution in the thickness direction using the CVD process and Si gradient steel sheet JNHF™ in 1998. Further in recent years, new Si gradient steel sheets JNSF™ and JNRF™ have been developed, in which the Si concentration distribution is optimized for different applications and frequencies. These high-silicon electrical steel sheets (Super Core™) are widely used as core materials including high-frequency reactors and high-speed motors. This paper introduces the characteristics and applications of the Super Core.

1. Introduction

In core materials of electrical equipment, low iron loss for high efficiency and high saturation magnetization to enable downsizing are generally required. Electrical steel (3% silicon steel), in which 3 mass% of Si is added to Fe, is a soft magnetic material with an excellent balance of iron loss, saturation magnetization, workability and other properties, and is used as a core material for various types of electrical equipment, including motors, reactors and transformers. In this following, mass% is denoted simply as % in this paper.

In recent years, use of high frequencies in inverters, switching power supplies, *etc*. and high rotating speeds in motors has advanced against the backdrop of progress in power electronics technology, and iron loss reduction at high frequencies has been strongly required to increase efficiency and downsize electrical equipment[1)]. Although higher Si contents and sheet thickness reduction are effective for reducing high-frequency iron loss, it is difficult to manufacture high Si steel sheets by cold rolling because the material is hard and brittle, and for this reason, approximately 3% Si had been considered to be the upper limit for the Si content of commercial electrical steels.

To overcome this problem, JFE Steel developed a continuous siliconizing process by chemical vapor deposition (CVD) and achieved industrial production of the 6.5% Si steel sheet JNEX™ for the first time in the world in 1993[2)]. On the other hand, for further downsizing and higher efficiency of electrical equipment, customers began to require materials with high properties surpassing the 6.5% Si steel sheet JNEX, and in 1998, JFE Steel developed the Si gradient magnetic material JNHF™ with lower high-frequency iron loss by applying the continuous siliconizing method to control the Si concentration distribution in the sheet thickness direction[3)]. More recently, the company also developed the new products JNSF™ and JNRF™ in which the Si concentration distribution is optimized for different applications and frequencies[4,5)]. These high-silicon electrical steel sheets (Super Core™) are widely used as core materials for high-frequency reactors and transformers and high-speed motors and continue to contribute to downsizing and higher efficiencies of electrical equipment. This paper introduces the features and applications of the high-silicon electrical steels sheets manufactured by JFE Steel.

2. Features and Applications of High-Silicon Electrical Steel Sheets

2.1 6.5% Si Steel Sheet JNEX™

Addition of Si to Fe increases resistivity and

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decreases iron loss. In particular, since the 1930s, it has been known that steel with a composition with a Si content of 6.5% has extremely high soft magnetic properties because magnetostriction is reduced to zero. However, it was difficult to manufacture 6.5% Si steel sheets by cold rolling because higher Si contents invite increased deformation resistance and an increased ductile-brittle transition temperature (DBTT). Although manufacturing methods for 6.5% Si steel sheets were studied, including a warm rolling method, rapid solidification method and siliconizing method, at present, an industrial production method utilizing the vapor phase siliconization method using CVD has been established[2)].

Figure 1 shows a schematic diagram of the continuous siliconizing line using CVD. In this method, first, the thickness of a low Si steel sheet, which is comparatively easy to be worked, is reduced by cold rolling. Next, continuous annealing is performed under an atmosphere containing $SiCl_4$ gas to induce a substitution reaction between the Fe in the steel sheet and the Si in the $SiCl_4$ gas, causing the Si to permeate into the steel sheet. A Si-rich layer is formed in the surface layer of the steel sheet by this reaction, and the 6.5% Si steel sheet JNEX with a uniform Si concentration in the thickness direction is then obtained by high-temperature diffusion treatment. Because grain boundary embrittlement can be suppressed by properly controlling the atmosphere in this siliconizing treatment, it has become possible to produce cores by slit processing, shearing and punching using JNEX at room temperature[6)].

JFE Steel mass produces JNEX with a sheet thickness of 0.1 mm (10JNEX900), which has a magnetic flux density of 1.0 T and iron loss $W_{10/1k}$ at the frequency of 1 kHz of approximately 19 W/kg. Thus, iron loss can be reduced by more than 50% in comparison with the iron loss values of approximately 40 to 60 W/kg of 3% Si steel with thicknesses of 0.2 mm to 0.35 mm. JNEX is suitable for use as a core material for high-frequency reactors, transformers and other devices in which high efficiencies are required, and is contributing to low acoustic noise in electrical equipment because its magnetostriction is substantially zero. It also has the interesting feature that its magnetic properties are not susceptible to changes due to stress and working[7)].

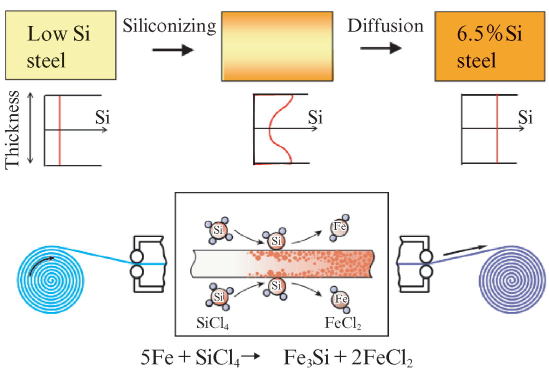

Fig. 1 Schematic diagram of continuous siliconizing line

2.2 Si Gradient Magnetic Material JNHF™

The continuous siliconizing method by CVD is a technique whereby Si is made to permeate into a steel sheet from the sheet surface. This means it is possible to produce materials with a nonuniform Si concentration distribution, that is, a high Si concentration at the surface and low Si concentration at the sheet center-of-thickness, by intentionally stopping the diffusion process after diffusion at the surface. JFE Steel discovered that this material displays unique magnetic properties, and succeeded in developing a new material with magnetic properties that could not be achieved with conventional electrical steel sheets, namely, the Si gradient electrical steel sheets JNHF[3)].

Figure 2 shows a schematic diagram of the Si concentration distribution in the sheet thickness direction of JNHF. Since the Si concentration of JNHF is 6.5% in the surface layer and low Si in the sheet center-of-thickness, the average Si concentration is small in comparison with the 6.5% Si steel sheet JNEX. In spite of this lower average Si concentration, JNHF has lower eddy current loss than the 6.5% Si steel sheet JNEX. **Figure 3** shows a comparison of the iron loss of the 6.5% Si steel sheet 10JNEX900 and the Si gradient

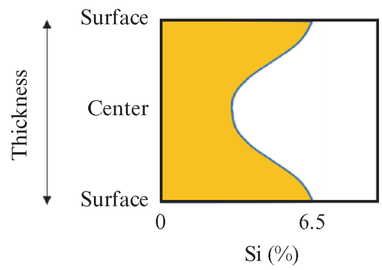

Fig. 2 Schematic diagram of Si concentration distribution of JNHF™ in thickness direction

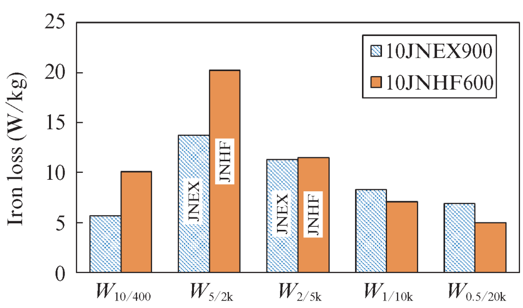

Fig. 3 Iron losses of JNEX™ and JNHF™ with 0.1 mm thickness

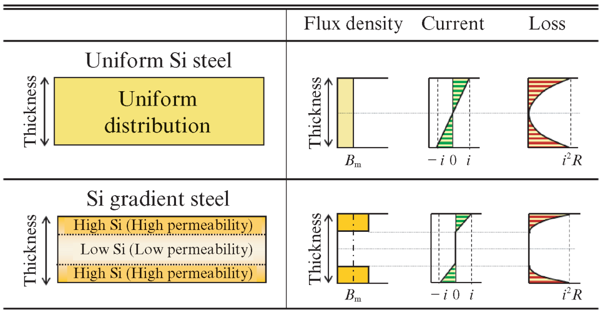

Fig. 4 Reduction of eddy current loss by Si concentration gradient

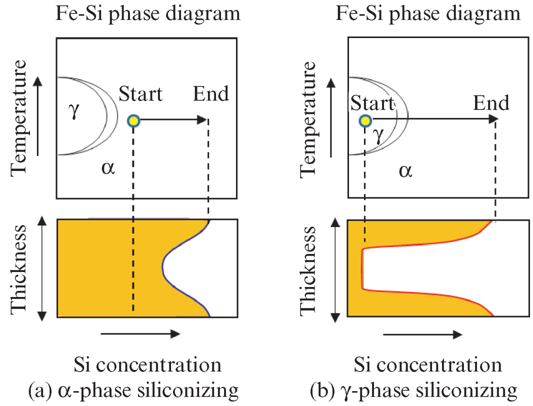

Fig. 5 Schematic diagram of α-phase and γ-phase siliconizing

electrical steel sheet 10JNHF600 (in both materials, sheet thickness: 0.1 mm). In the frequency region of 10 kHz and over, where eddy current loss becomes controlling, JNHF shows low iron loss, surpassing that of the 6.5% Si steel sheet JNEX.

Figure 4 shows the mechanism of eddy current loss reduction by the Si concentration gradient. In the case of AC excitation of a Si gradient magnetic material, the flux concentrates in the surface region, where magnetic permeability is high due to the high Si concentration, and the induced electromotive force and the accompanying eddy current also concentrate in the surface layer[8]. This is a type of skin effect which is induced by the Si concentration gradient, and it is thought that JNHF shows low eddy current loss due to this effect.

Because Si is a nonmagnetic element, JNHF, which has a small average Si content, also has the feature of higher saturation magnetization in comparison with the 6.5% Si steel sheet JNEX. Because its lower Si content also contributes to improved workability, JNHF can also be applied easily to the motor core punching process. JNHF is a suitable material for high efficiency and downsizing of high-frequency devices, and is used in high-frequency reactors and ultra-high-speed motors.

2.3 Si Localized Material JNSF™

As described above, in Si gradient magnetic materials, eddy current loss is reduced by the Si concentration distribution in the sheet thickness direction. Therefore, assuming that the Si concentration distribution can be made even steeper and Si can be localized only in the vicinity of the surface, it can also be thought that a further reduction of eddy current loss is possible. Because the Si content in the sheet center-of-thickness can be reduced by the steeper Si concentration gradient, improvement of saturation magnetization by the decrease in the average Si content can also be expected. However, the continuous siliconizing method by CVD is carried out at an extremely high temperature, which makes it difficult to suppress diffusion of Si from the surface to the center-of-thickness if the conventional technique is used.

To overcome this problem, JFE Steel developed a new siliconizing method called γ-phase siliconizing, in which Si diffusion is suppressed by controlling the crystallographic structure of the steel sheet during continuous siliconizing treatment[4]. **Figure 5** shows a schematic diagram of the conventional siliconizing method and the γ-phase siliconizing method. In the conventional siliconizing method in Fig. 5 (a), the crystal structure of the steel sheet is the α-phase (fcc), and it was difficult to reduce the Si concentration in the center-of-thickness layer due to the high Si diffusion rate. In contrast, in the γ-phase siliconizing method in Fig. 5 (b), the crystal structure of the steel sheet at the start of siliconizing was controlled to the γ-phase (bcc) by optimizing the material alloy design and siliconizing conditions. Because the γ-phase has the densest packing structure, Si diffusion is delayed. As a result, Si diffusion during siliconizing treatment was remarkably suppressed, and localization of Si to the surface layer region was materialized.

In the Si localized electrical steel sheet JNSF produced by the γ-phase siliconizing method, the high Si region is localized to the vicinity of the surface layer, so the material has the distinctive feature of an extremely steep Si concentration gradient in comparison with conventional Si gradient magnetic materials. This has made it possible to achieve low Si in the center-of-thickness region, and thereby reduce eddy current loss and improve saturation magnetization. **Figure 6** shows the magnetic properties of JNSF. JNSF with a sheet thickness of 0.15 mm shows high-frequency iron loss comparable to that of the 6.5% Si steel sheet with a thickness of 0.1 mm in spite of its thicker thickness. In addition, JNSF also displays high saturation magnetization of approximately 2.0 T, which is an improvement of about 10% in comparison with the

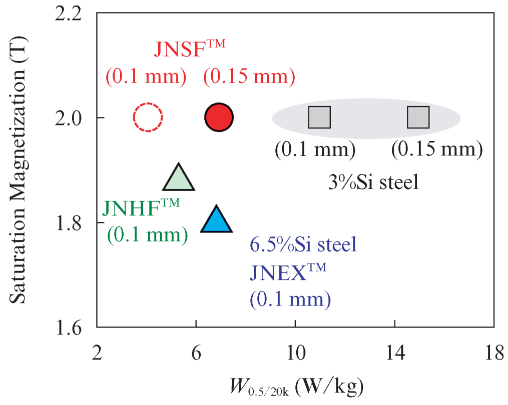

Fig. 6 Magnetic properties of JNSF™

6.5% Si steel sheet. Based on these features, JNSF is considered to be a suitable material for high frequencies and downsizing of high-frequency reactors and other devices with similar requirements.

2.4 High Magnetic Flux Density Si Gradient Magnetic Material JNRF™

In recent years, there has been increasing interest in CO_2 emission reduction and energy conservation from the viewpoint of preventing global warming, resulting in heightened demand for higher efficiency in motors. Since the electric power consumed by motors accounts for approximately 60% of total electric power consumption in Japan, a trial calculation has shown that a hypothetical 1% improvement in the efficiency of motors in Japan would lead to an energy saving equivalent to the output of one 500 000 kW class nuclear power plant[9]. In the automotive sector, electrification of vehicle power trains is progressing, and higher efficiency is strongly demanded in the traction motors of hybrid electric vehicles (HEV) and electric vehicles (EV). In addition to low iron loss at frequencies of 50 Hz to 1 kHz, high saturation magnetization is required in the core materials for these motors.

One strong point of the Si gradient electrical steel sheets JNHF and JNSF is higher saturation magnetization in comparison with the 6.5% Si steel sheet JNEX. However, these materials are not necessarily the optimum materials for motor applications, as they were designed to achieve low iron loss at frequencies of 10 kHz and higher, which is important in high-frequency reactors. Because the ratio of hysteresis loss in total iron loss is high in the 50 Hz to 1 kHz region, which is the drive frequency range of general motors, it was necessary to change the material design to a form that would be suitable for reduction of hysteresis loss.

Based on this background, JFE Steel developed the high magnetic flux density Si gradient electrical steel sheet JNRF[5]. In the development of this material, the average Si content was reduced from the viewpoint of increasing saturation magnetization, and the Si concentration distribution in the sheet thickness direction was reviewed in terms of iron loss reduction at 50 Hz to 1 kHz. In addition to these changes, the texture (crystal orientation) was also improved to increase the magnetic flux density and reduce hysteresis loss in the high magnetic field region. The manufacturing conditions were also optimized in this development, and a texture improvement technique that reduces grains with the {111} orientation, which adversely affects magnetic properties, and increases grains with the {100}, {110} orientation was applied.

Figure 7 shows the magnetic properties of JNRF arranged by iron loss $W_{10/400}$ at 1.0 T and 400 Hz, and the magnetic flux density B_{50} at the magnetic field strength of 5 000 A/m. In addition to low iron loss superior to that of the existing Si gradient magnetic material JNHF, JNRF also shows a high magnetic flux density comparable to that of 3% Si steel sheets.

Figure 8 shows the appearance of a small motor core which was manufactured by punching and interlocking using JNRF with a thickness of 0.1 mm[10]. Because the workability of JNRF was further improved by reducing the average Si content, this material is also suitable for punching and interlocking of motor cores with complex geometries.

In addition to its low iron loss characteristics at 50 Hz to 1 kHz, JNRF has saturation magnetization equal to that of 3% Si steel sheets and excellent work-

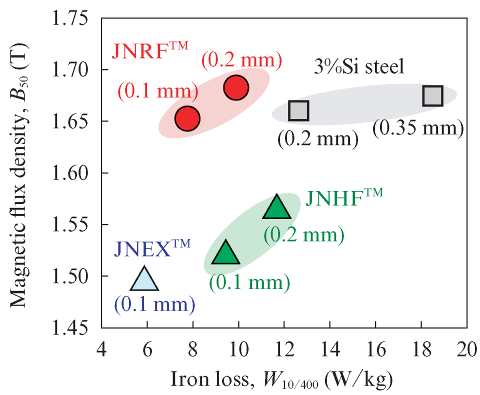

Fig. 7 Magnetic properties of JNRF™

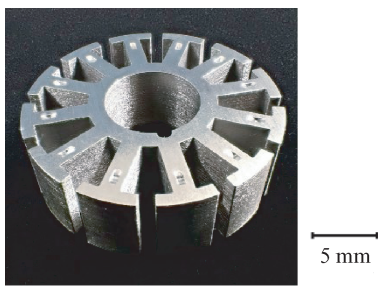

Fig. 8 Motor core made of JNRF™ with 0.1 mm thickness

ability. JNRF is considered to be an ideal core material for motors in which high efficiency and downsizing are strongly required. Application to high-frequency motors in the HEV/EV, drone and aeronautical fields is under study.

3. Comparison of Properties of High-Silicon Electrical Steel Sheets

Table 1 shows the magnetic properties of JFE Steel's high-silicon electrical steels sheets (Super Core)[3]. As comparison materials, the table also shows examples of the properties of an ultra-thin-gauge grain-oriented electrical steel and a Fe-based amorphous material, which are representative soft magnetic materials for high-frequency use. Although the amorphous material shows low iron loss over a wide frequency range, its magnetostriction is large and saturation magnetization is low, which means excessive acoustical noise in electrical equipment and the large size of cores are problems. As an additional problem, since the sheet thickness is extremely thin and the material is brittle, it is difficult to produce motor cores by punching processing. While the ultra-thin-gauge grain-oriented electrical steels sheet has high saturation magnetization, its high-frequency iron loss is also large, so decreased efficiency in electrical equipment is a problem. Moreover, this material is difficult to apply to rotating machinery due to its poor magnetic properties in directions other than the rolling direction. In contrast with this, Super Core features an excellent balance of high-frequency iron loss, saturation magnetization and workability, and thus makes it possible to achieve high efficiency and downsizing when applied to high-frequency reactors and high-speed motors.

The saturation magnetization and suitable frequency regions for each of JFE's high-silicon electrical steels sheets are shown schematically in **Fig. 9**. The 6.5% Si steel sheet JNEX has a somewhat low saturation magnetization, but displays low iron loss over a wide range of frequencies. Since it also has the advantage of low magnetostriction, a noise reduction effect has been reported in reactors, motors and other electrical equipment[3,11]. The Si gradient electrical steel sheets JNHF and JNSF are suitable materials when higher saturation magnetization is necessary in high-frequency applications. Because the eddy current loss of these materials is reduced by the effect of the Si concentration gradient, they show low iron loss equal or superior to that of the 6.5% Si steel sheet JNEX, particularly in the 10 kHz to 20 kHz frequency region, where eddy current loss is the controlling factor for iron loss. When high saturation magnetization is necessary in lower frequency applications such as motors, the high magnetic flux density Si gradient electrical steel sheet JNRF is suitable. This material has saturation magnetization equal to that of 3% Si electrical steels sheets and also shows lower iron loss than JNHF and JNSF in the region up to several kHz. High efficiency and downsizing can be achieved by appropriate use of these materials, considering the application and design.

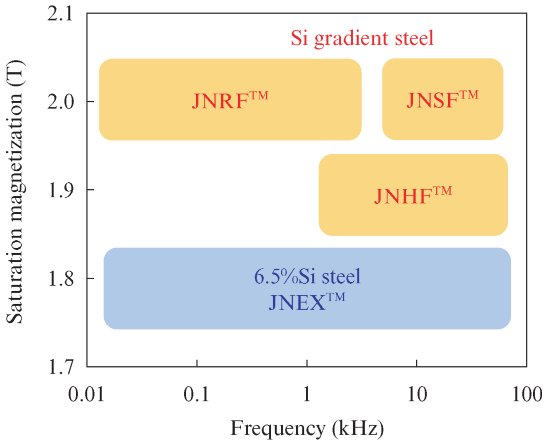

Fig. 9 Saturation magnetizations and suitable frequencies of high-silicon electrical steel sheets

Table 1 Magnetic properties of high-silicon electrical steel sheets "Super Core™"

Material	Thickness (mm)	Saturation magnetization (T)	Iron loss (W/kg) 50 Hz 1.0 T	400 Hz 1.0 T	5 kHz 0.2 T	10 kHz 0.1 T	20 kHz 0.05 T	Magnetostriction at 1.0 T, 400 Hz ($\times 10^{-6}$)
10JNEX900	0.10	1.8	0.5	5.7	11.3	8.3	6.9	0.1
10JNHF600	0.10	1.9	1.1	10.1	11.2	7.1	5.4	3.1
15JNSF950	0.15	2.0	1.5	15.0	14.9	9.7	7.0	2.8
10JNRF	0.10	2.0	0.6	7.5	13.4	10.6	8.6	2.3
Grain-oriented 3%Si steel*	0.10	2.0	0.7	6.4	20	18	14	− 0.8
Fe-based amorphous	0.025	1.5	0.1	1.5	8.1	3.6	3.3	27

* Magnetic properties in the rolling direction

4. Examples of Application of Si Gradient Magnetic Materials to Motors

4.1 Needs for Motor Core Materials

With the progress of motor downsizing and use of higher frequencies, materials that satisfy both high magnetic flux density and low iron loss are demanded in motor core materials. The high magnetic flux density Si gradient electrical steel sheet JNRF described in section 2.4 satisfies high magnetic flux density and low iron loss at 50 Hz to 1 kHz, and thus is considered to be a suitable material for motor applications. Therefore, a small-scale motor for use in evaluation of motor properties was prepared, and the effect of material properties on motor properties was evaluated.

4.2 Motor Evaluation

In this study, the target of the evaluation was an interior permanent magnet (IPM) motor, assuming the traction motors used in EV and HEV, in which downsizing and higher output are progressing. **Table 2** and **Fig. 10** show the specification and a schematic diagram of the evaluation motor. As the core material, three types of electrical steels sheets were used, 20JNEH1500 (3% Si steel sheet), 10JNHF600, and 10JNRF. The thicknesses of the materials were 0.2 mm, 0.1 mm and 0.1 mm, respectively. After the materials were punched, motor cores were assembled by fixing by interlocking, and the evaluation motors were completed by winding, *etc*. The obtained motors were then connected to the measuring instrument, and the motors were evaluated using maximum efficiency control.

Figure 11 shows the motor efficiency maps obtained in this test[12]. The motors using the Si gradient electrical steel sheets 10JNHF600 and 10JNRF showed higher motor efficiency than the motor using the 3% Si steel sheet. In particular, a large improvement in efficiency was confirmed under the high-speed rotation condition, in which the ratio of iron loss in motor loss becomes large, and the motors using the Si gradient electrical steel sheets displayed high efficiency exceeding 95% in the region of 10 000 rpm and higher.

On the other hand, a decrease in maximum torque was observed in the motor using 10JNHF600. This is considered to be due to the somewhat lower saturation magnetization of 10JNHF600 compared to 3% Si steel sheet. In contrast, with the motor using the high saturation magnetization material 10JNRF, maximum torque equal to that of the motor using the 3% Si steel sheet was obtained.

Based on the results described above, JNRF is con-

Table 2 Specification of test motor

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

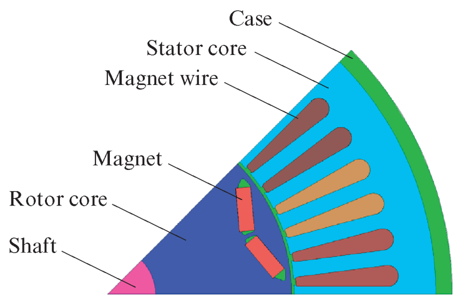

Fig. 10 Schematic diagram of test motor

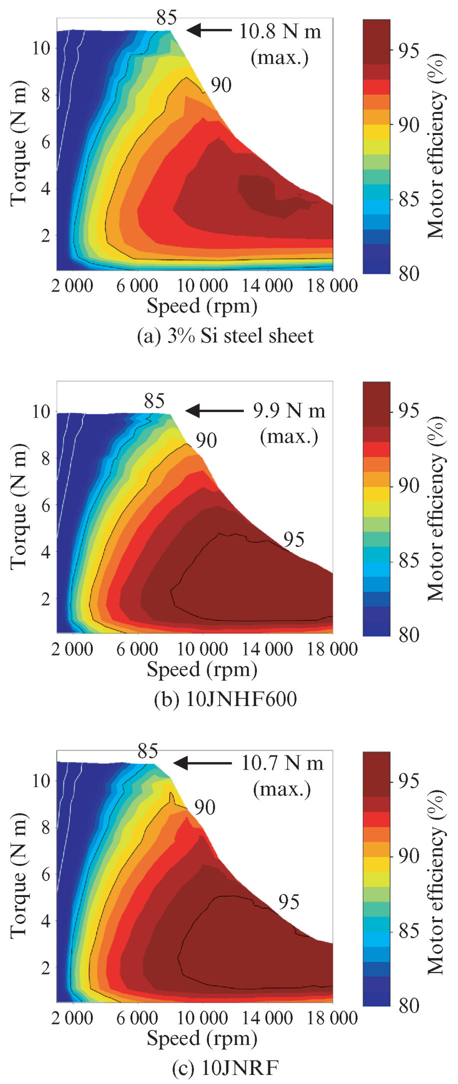

Fig. 11 Results of motor efficiency evaluation

sidered to be a suitable material for the cores of high-speed motors, and can make a large contribution to motor downsizing and high efficiency.

5. Conclusion

In 1993, JFE Steel constructed a continuous siliconizing line using CVD and achieved the only industrial production of the 6.5% Si steel sheet JNEX in the world. When the continuous siliconizing line was started up, its only role was to increase the Si content of steel sheets, but its positioning was greatly expanded by innovation, namely, the development of the Si gradient magnetic materials. The current continuous siliconizing line also plays an important role by enabling free control of the Si concentration distribution in the sheet thickness direction, and is continuing to give birth to unique soft magnetic materials that could not be achieved with the conventional method, such as JNHF, JNSF and JNRF. These materials are widely used as core materials for high-frequency reactors, high-speed motors and other advanced products, and are continuing to contribute to high efficiency and downsizing of electrical equipment, together with CO_2 emission reduction and energy conservation. Since Super Core also has the potential for further evolution, JFE Steel will also continue research and development for the creation of new high performance in the future.

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