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Non-oriented Electrical Steel Sheet and Its Application Technology for the Traction Motors of Hybrid/Electrical Vehicles

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Abstract

Non-oriented electrical steel (NO) is widely used as a motor core material since, economically, it meets requirements for high-efficiency, high-power motors. The market for hybrid electrical vehicles (HEV) and electrical vehicles (EV) has been expanding and the models of HEV/EV have been increasing; thus, performance requirements of NO for traction motor cores have diversified. In this paper, we introduce newly developed NOs and its application technology.

1. Introduction

Vehicles in the 21st century need to be environment friendly. To reduce gas emissions that contribute to global warming and improve fuel efficiency, the hybrid technology to combine an engine and electric motor was developed, and, in 1997, the world-first mass-produced hybrid electric vehicles (HEVs) were put on the market. The mass production of plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) whose percentage of electricity use was higher began. The International Energy Agency (IEA) estimates[1] that approximately 10% of passenger vehicles and other types of vehicles will be EVs in 2030.

Traction motors for electric vehicles such as HEVs, PHEVs, and EVs (hereinafter EV traction motors) are the key parts of the drive mechanism that takes the place of engines. Electrical steel sheets are an important functional material type that significantly improve the EVs' drive performance and fuel efficiency as iron core materials. This paper describes the latest electrical steel sheets (materials) that support higher performance of EV traction motors along with technologies for using them.

2. Requirements for Electrical Steel Sheets for EV Traction Motors

EV traction motors, unlike general motors, need to have high torque performance for start-up and climbing hills and high-speed rotation characteristics in driving at maximum speed. They also need to be highly efficient in the speed range in which the vehicles are most frequently driven. In addition, for HEVs, it is important that a motor can be installed in a limited space, so EV traction motors need to be smaller and lighter and they need to be highly efficient compared to other types of motors for other applications (refer to **Fig. 1**).

In order to increase the torque of a motor, it is important to pass a larger driving current through the motor windings and increase the magnetic flux that interlinks with the windings. The electrical steel sheet used needs to have high magnetic flux density for a given magnetic field intensity, that is to say, high permeability. An effective way to increase the magnetic flux is to narrow the clearance between the rotor and stator to reduce the magnetic resistance. Thus, electrical steel sheets need to have excellent workability.

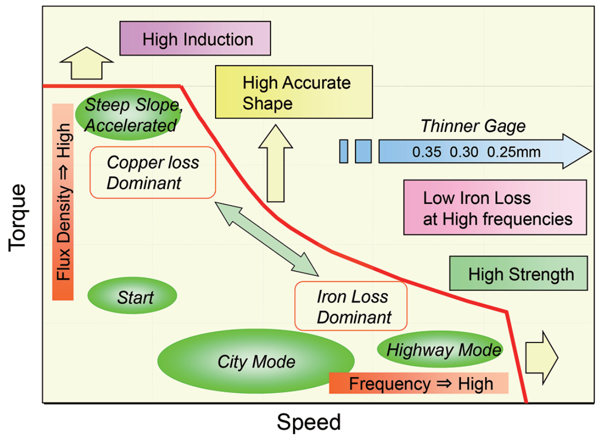

Fig. 1 Performance requirements for electrical steel sheet for drive motors of EV/HEV

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The output of a motor is expressed as the product of the torque and rotational speed of the motor. Therefore, to reduce the motor size, it is effective to increase the rotational speed. As the rotational speed increases, the frequency of the driving current rises. Therefore, the iron loss of an electrical steel sheet under high-frequency excitation must be low. In addition, motors are excited by inverters, so the iron loss at carrier frequency (high frequency) needs to be low. When a motor is run at a high speed, large centrifugal force works, so electrical steel sheets used for rotors need to be highly strong.

To improve fuel efficiency in an effective way, it is important to reduce the iron loss and improve the magnetizing properties in the most frequently used drive range (intermediate-level magnetic flux density and frequency). On the traction motor of an HEV, if the motor runs idle without drive current while the vehicle is driven by the internal combustion engine, low iron loss is more important for minimizing the power loss during idle running.

3. Electrical Steel Sheets Suitable for EV Traction Motors

Besides electrical steel sheets, sheets of 6.5%Si steel, a Co-Fe alloy, and a Ni-Fe alloy are also used as the materials for motor cores. However, few of them satisfy the technical characteristics required for EV traction motors more economically and in a better-balanced way than electrical steel sheets do. Therefore, non-oriented electrical steel sheets (NO) are actually used for motors. Grain-oriented electrical steel sheets (GO) may be used, but special measures[2)] have to be taken depending on the properties of the materials.

Usually, to reduce the iron loss of NO, the contents of alloying elements (e.g., Si) are increased and the thickness is reduced to suppress eddy currents in steel sheets. However, a higher alloying content reduces the saturation magnetic flux density at the same time and thinner sheets reduce the productivity of cores. Therefore, products need to be developed while these effects are balanced. For example, to satisfy both low iron loss and high magnetic flux density, it is effective to adjust the alloying contents and to control the crystal orientations[3, 4)] and grain size.[5)]

Nippon Steel Corporation has been developing a new series of non-oriented electrical steel sheets that satisfy requirements as electrical sheets for HEV/EV traction motors. **Figure 2** shows example magnetic properties of the developed product series of high-efficiency non-oriented electrical steel sheets (HIEXCORE™ and THINNER GAUGE HIEXCORE™ HX) in which magnetic flux density B_{50} (the flux density under a magnetizing force of 5 000 A/m) has been improved at the same level of iron loss for higher motor torque.

Figure 3 shows example analysis results of the iron loss of motors using thin NO developed for EV traction motors. This analysis model is a benchmark of interior permanent magnet (IPM) motors determined by the Institute of Electrical Engineers of Japan.[6)] Figure 3 clearly shows that, for the thin NO, the higher the motor's rotational speed is, the higher the iron loss reduction effect is as compared with conventional materials.

Figure 4 shows the magnetic and mechanical properties of the high-tensile electrical steel sheet series (HIGH TENSILE STRENGTH HILITECORE™ HXT) suitable for use in high-speed rotors. Although the iron loss at high frequency ($W_{10/400}$) (iron loss under excitation of 1.0 T and 400 Hz) is inferior to that of general-purpose steel materials, the tensile strength is 1.5 times that of general-purpose steel materials. They are used for commercially available EV traction motors. Nippon Steel has also been developing high-tensile NO whose iron loss is reduced to the level of general-purpose steel materials.[7)] The developed high-tensile NO is suitable for the rotor cores of IPM motors although its iron loss is somewhat inferior. It is difficult to narrow the width of a rotor bridge that retains a permanent magnet from the perspective of durability at high-speed rotation. Using high-tensile NO can make design with narrower bridge width possible, which improves the efficiency of motors[8)] (see **Table 1**). This is mainly because, among magnetic flux, leakage flux to the bridge section is reduced, which increases the motor torque constant, which reduces copper loss.

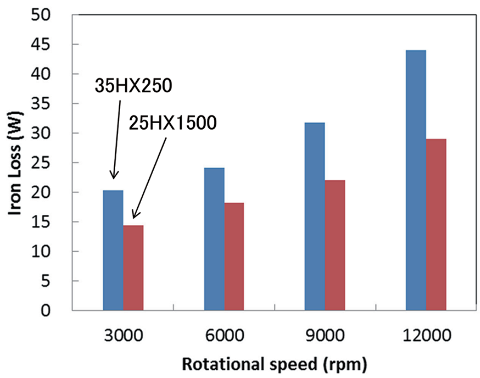


Fig. 3 Iron loss analysis of the model motor in load operation

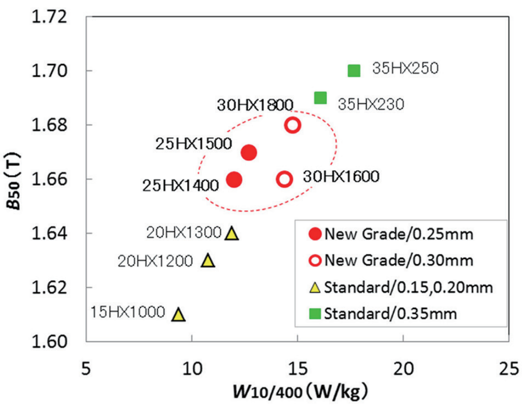


Fig. 2 Magnetic properties of THINNER GAUGE HIEXCORE™ for high efficiency motor

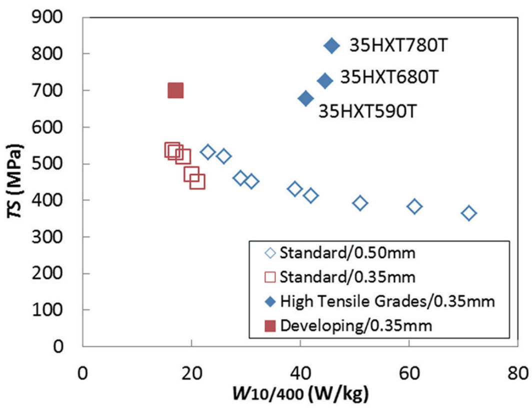


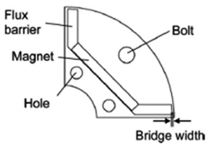
Fig. 4 Magnetic and mechanical strength properties of HIGH TENSILE STRENGTH HILITECORE™ HXT

Table 1 Plastic deformation limit rotational speed and motor efficiency as a bridge width of rotor core

Rotor core material	YS (MPa)	Brige width (mm)	Speed* (rpm)	Efficiency** (%)
35A300	320	0.5	17000	91.8
	320	1.0	25000	91.1
35HXT680T	659	0.5	25000	91.6

* Result of deformation analysis by 3D-FEM

** Result of motor load experiment at 5400 rpm



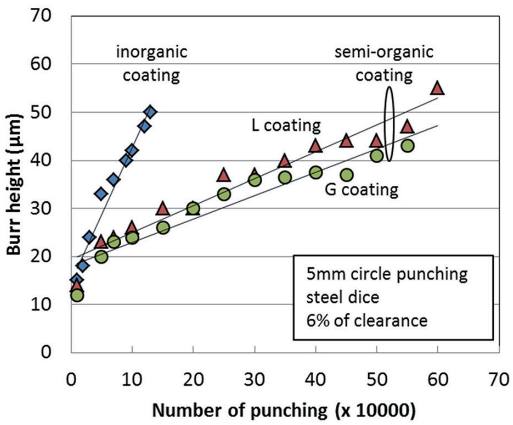


Fig. 5 Punching workability of electrical steel sheet
L coating is chromite based insulating coating with organic resin.
G coating is phosphate based insulating coating with organic resin.

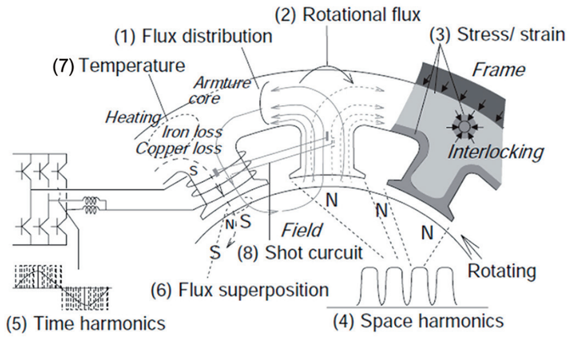


Fig. 6 Factors in real motor core to increase iron loss

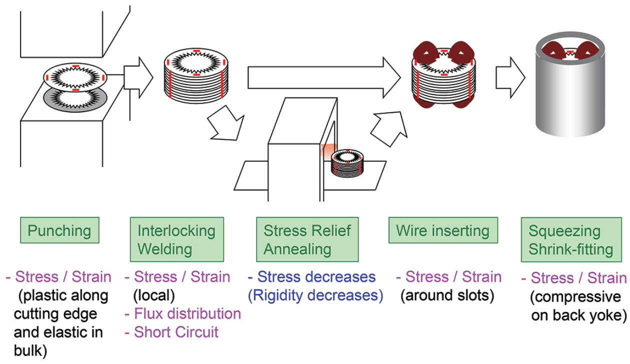


Fig. 7 Iron loss deterioration in motor manufacturing process

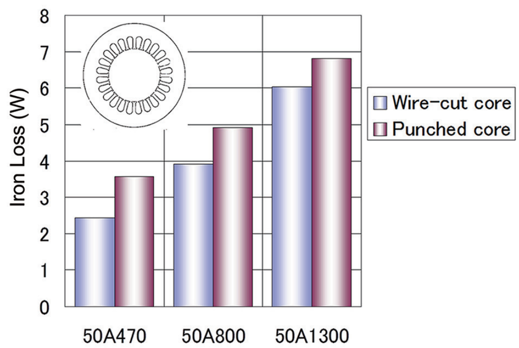


Fig. 8 Effect of punching processing on motor core loss

4. Environment-friendly Insulating Coatings for Electrical Steel Sheets with Excellent Punching Workability

A non-oriented electrical steel sheet used for motor cores has an insulating coating with a thickness of 1 to 2 μm formed on the surface to make punching easier and to prevent inter-laminar short circuiting. To that end, organic/inorganic coatings (named L coating by Nippon Steel) containing trivalent chromium compounds and organic resin have been used for more than 40 years around the world.[9] Meanwhile, in recent years, awareness of the environment has been growing as represented by the RoHS in Europe. Therefore, Nippon Steel has developed new environment-friendly insulating coating, G coating, that does not contain chromium compounds. G coating provides higher insulation resistance than conventional coatings containing chromium compounds. They have various other advantages, for example, excellent punching workability as shown in **Fig. 5**. In addition to this, they resist heat and solvents well since coatings sometimes need to have resistance in actual service environments.

5. Electrical Steel Sheet Application Technologies to Support the Performance of EV Traction Motors

In accordance with international standard measurement method IEC60404-2, the magnetic properties of an electrical steel sheet are measured under ideal conditions of a uniform alternating magnetic field in a prescribed one direction, no stress, and a sinusoidal magnetic flux density. However, in reality, various factors that increase iron loss work on an electric steel sheet as shown in **Fig. 6**. These factors are: (1) uneven magnetic flux originating in the core structure; (2) rotational magnetic flux; (3) compressive stress due to deformation by punching and shrink-fitting of the core; (4) space harmonics; (5) time harmonics caused by the power supply or other factors; (6) superposition of the magnetic flux due to the magnet or the magnetic field from the windings; (7) uneven temperatures, and (8) inter-laminar short circuits at the clumped section.[10–24]

Among the aforementioned iron-loss-increasing factors, plastic deformation and compressive stress are unavoidably introduced to the motor core during the motor core manufacturing processes shown in **Fig. 7** and they significantly increase iron loss. We fabricated a stator core with an outer diameter of 120 mm and 24 slots by punching and wirecut electrical discharge machining that would not cause deformation as a result of processing. **Figure 8** shows iron loss[11] measured by our unique rotating iron loss simulator.[12] The figure shows that, although the increase in iron loss differs depending on the type of steel sheet, the core iron loss increases as a result of deformation by punching.

6. Electromagnetic Field Analysis Considering Factors That Increase Iron Loss[20)]

In recent high-efficiency motor design, models using complicated magnetic circuits are mainstream (e.g., interior permanent magnet), so the finite element method and other electromagnetic field analysis methods are generally used. Considering the aforementioned factors that increase iron loss in such motor analysis, the motor performance can be estimated at high accuracy and factors that deteriorate loss of motors and other properties can be efficiently identified along with effects of countermeasures.

Table 2 compares the iron loss measurement result when a stator core that was made by punching a 50H270 material was tested with a rotating iron loss simulator[12)] with the core iron loss value calculated by an electromagnetic field analysis technique of Nippon Steel.[14)] They match well, showing that the analysis technique is appropriate. Next, this analysis technique was applied to calculate iron loss considering all of the following: the influence of magnetic anisotropy of an electrical steel sheet;[22, 23)] deformation due to processing;[24)] and space harmonics. Each influential factor was excluded one by one to calculate the core iron loss in a state simulating the ideal state.

Figure 9[14)] shows the increase in iron loss (%) caused by each of the analysis conditions when assuming that the difference in iron loss between the ideal state and the case where all of the three iron-loss-increasing factors are considered is 100%. The figure shows that the influence of deformation due to processing is the largest, which indicates that annealing to remove deformation of a core can significantly improve iron loss. The influence of the harmonics comes second. The influence of the anisotropy of the material is rather small at approximately 10% for this motor core. However, for a stator core for an EV/HEV, a segment core may sometimes be used. In such a case, the influence on the iron loss value may be larger depending on the relationship between the main flux of the core and the magnetic anisotropy of the electric steel sheet. Electromagnetic field analysis can be used to find an appropriate combination of the shape of a core and magnetic anisotropy.

In addition, EV traction motors and high-efficiency air conditioner motors are driven by power supplied from inverters. It is important in motor electromagnetic field analysis under actual service conditions to consider influence of excitation by complicated magnetic flux density when harmonics from an inverter superpose on space harmonics from the motor. Ring samples (outer diameter: 47 mm, inner diameter: 33 mm, and core thickness: 7 mm) for which electrical steel sheets in four steel grades (35A210, 35A300, 50A470, and 50A1300) were used as iron cores were made. They were excited by complicated magnetic flux density that was equivalent to that in the actual service state of motor cores to measure iron loss. The values were compared with those calculated using Nippon Steel's electromagnetic field analysis technique. **Figure 10** is a scatter diagram showing the comparison results when the pulse width modulation of the inverter when many harmonics contents are contained is 0.4.[21)] Regardless of the steel grade and waveform originating in the space harmonics, the calculated results match the measured values at a high accuracy of 5%, showing that the technique is accurate in practice. This technique may contribute, in addition to adoption of a model that can evaluate the influence of eddy currents that harmonics induce in an electrical steel sheet, to achieving high accuracy of iron loss analysis and high measurement accuracy of

Table 2 Calculated value and an experimental value of motor core loss

	Experimental	Calculation
Motor core loss (W/kg)	0.24	0.25

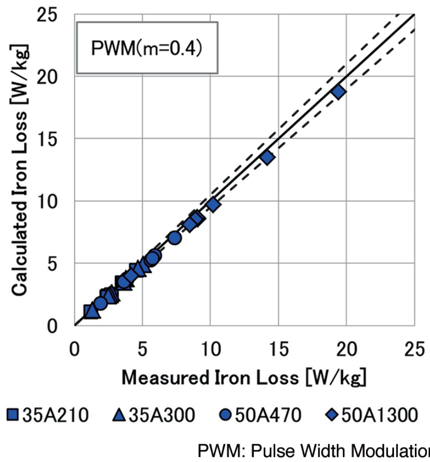
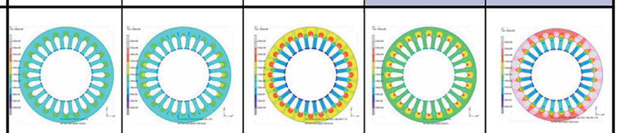


Fig. 10 Measured and calculated iron losses excited by PWM voltage waveform, modulation ratio 0.4

Analysis condition						
	Anisotropy	Ignored	Considered	Ignored	Ignored	Considered
	Stress	Ignored	Ignored	Considered	Ignored	Considered
	Harmonics	Ignored	Ignored	Ignored	Considered	Considered
Iron loss contour maps						
Contribution*			10%	50%	40%	100%

* Ratio of iron loss increase due to various factors

Fig. 9 Analysis for iron loss in motor core with various conditions

magnetic properties input to the electromagnetic field analysis.

7. Improvement of the Traceability of Magnetic Property Measurement of Electrical Steel Sheets Aiming at the Global Market

Energy saving through motorized vehicles and spread of high-efficiency air conditioners is a global movement, so the percentage of high-performance non-oriented electrical steel sheets traded on the global market may rise. Typical magnetic properties of electrical steel sheets are iron loss (W/kg) and magnetic polarization (T) evaluated by measurement methods specified in the IEC standards. Designers in motor manufactures select NO materials suitable for the development of high-efficiency motors while referring to magnetic properties listed in catalogs issued by electrical steel sheet manufacturers. Under such circumstances, the electrical steel sheet sector of Nippon Steel has been working so that magnetic properties provided to customers are traceable to the national measurement laboratories.

Property values of non-oriented electrical steel sheets are evaluated in accordance with IEC60404-2 ("Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of an Epstein frame"). The National Physical Laboratory (NPL) in the U.K., Physikalisch-Technische Bundesanstalt (PTB) in Germany, Istituto Nazionale di Ricerca Metrologica (INRiM) in Italy, and other national measurement laboratories have performed round-robin tests to ensure that the reproducibility of the measurement method in accordance with the IEC standard is within a certain range. Since there is no such national measurement laboratory in Japan, Nippon Steel has obtained magnetic property reference samples from the aforementioned national laboratories and uses them to evaluate the accuracy of the in-house magnetic property measurement equipment. In addition to that, Nippon Steel has obtained a Japan Accreditation Board (JAB) certification for JIS standards specifying magnetometry, and it is certified that Nippon Steel's equipment, calibration, and management are appropriate.

Nippon Steel will continue developing new high-performance electrical steel sheets in the future while taking into consideration motor manufacturer and customer needs. Providing highly reproducible and reliable property values for such sheets can assist motor designers around the world in improving their design accuracy and rapidly adopting new high-performance electrical steel sheets. This will accelerate the development of high-performance motors, and may contribute to movement toward high-efficiency electric power utilization.

8. Conclusions

This paper introduced the development of non-oriented electrical steel sheets for traction motors for HEVs and EVs along with studies on technologies for using such sheets. To realize high-efficiency motors with high power density, thinning electrical steel sheets, increasing their tension, and applying insulating coatings with excellent workability are effective measures. In addition, the performance of motors is affected by the service environment. Therefore, it is important in technologies for using electrical steel sheets to consider measures to improve the performance of equipment by clarifying types of loss of motors and their causes using various analysis and evaluation techniques.

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