NIPPON STEEL TECHNICAL REPORT No. 103 MAY 2013

Technical Report

UDC 669 . 14 . 018 . 583 : 629 . 113 . 6

Electrical Steel Sheet for Traction Motor of Hybrid/Electrical Vehicles

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Abstract

15 years have passed since the first commercial hybrid electric vehicle (HEV) was sold. Meanwhile, the market has been expanding and the type of HEV/EV has been increasing, and then demands to electrical steel sheet for traction motor cores of HEV/EV has become diversified. In this paper, the demands to electrical steel sheet for traction motor cores of HEV/EV are reconfirmed, and then newly developed electrical steel sheet and the application techniques of electrical steel sheet are informed.

1. Introduction

Fifteen years have passed since the world's first production model hybrid electric vehicle (HEV) was introduced to the market. Since then the market for HEVs has expanded with HEV models increasing in number. Today, electric vehicles (EVs) and plug-in HEVs are being manufactured on a commercial basis. Compared with the conventional gasoline engine, the electric motor has better response and allows more precise torque control. Therefore, we expect the scope of application of electric motors to continue to expand. Accordingly, improving the properties of the electrical steel sheets used in the cores of EVs/HEVs traction motors is expected to enhance the performance of the traction motor and improve EV/HEV fuel efficiencies. In this report, we describe the latest development and technology for application of electrical steel sheets that enhance the performance of traction motors for HEV/EV.

2. Performance of HEV/EV Traction Motors and Required Properties of Electrical Steel Sheets used in Traction Motors

Unlike the ordinary motor, the HEV/EV traction motor is required to have a high torque characteristic to allow for quick starting of the vehicle and powerful hill climbing, and a high revolution characteristic to permit the vehicle to attain a high top speed. The traction motor is also required to be especially efficient at the speed range in which the vehicle is most frequently driven. In addition, the traction motor needs to be not only economical but also compact in size and light in weight, especially for HEVs that have a comparatively small space for the motor (**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. For reducing the motor size, the electrical steel sheet used is required to have a high magnetic flux density. An effective way to increase the magnetic

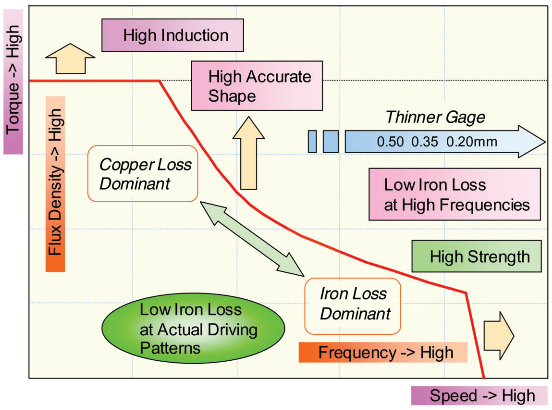

Fig. 1 Required properties for main motors of HEV/EV

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flux is to narrow the clearance between the rotor and stator, thereby reducing the magnetic resistance. Thus, the accuracy of working on the electrical steel sheet is also important.

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 while maintaining the output that is proportional to the torque, it is necessary to increase the rotational speed. When the rotational speed is increased, the excitation frequency of the electrical steel sheet rises; hence, the iron loss of the electrical steel sheet at high frequencies must be sufficiently small. In addition, when the motor is run at a high speed, a large centrifugal force acts on the peripheral part of the rotor; therefore, the electrical steel sheet used in the rotor is required to have adequate strength.

In order to meet the above requirements, Nippon Steel Corporation developed a new series of non-grain-oriented electrical steel sheets.[1] **Fig. 2** shows examples of the magnetic properties of the high-efficiency non-grain-oriented electrical steel sheet series whose magnetic flux density B50 (i.e., magnetic flux density at the magnetizing force of 5,000 A/m) was improved to obtain a higher motor torque without causing increased iron loss. **Fig. 3** shows examples of the magnetic properties of the thin-gauge electrical steel sheet series for use at high frequencies that reduced the iron loss caused by high frequency excitations. Compared with the conventional 35H/50H series, the new thin-gauge series (15HTH/20HTH) reduced iron loss W10/400 while limiting the decline in magnetizing force H10/400. **Fig. 4** shows examples of the magnetic and mechanical properties of the high-tensile electrical steel sheet series suitable for use in high-speed rotors. It attained a tensile strength two or more times that of the conventional series while minimizing the increase in iron loss W10/400. The new series of electrical steel sheets are used in HEV/EV traction motors currently sold on the market.

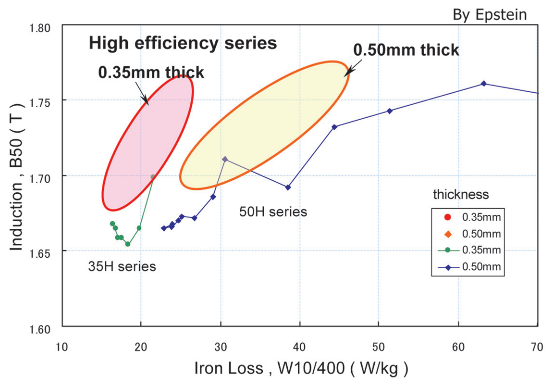


Fig. 2 Magnetic properties of high efficiency series

3. Magnetization Process of Electrical Steel Sheet and Important Material Factors

Many of the HEV/EV traction motors available on the market are IPM motors with a permanent magnet embedded in the rotor. In an effort to reduce the use of the rare earth elements used in the motor's magnets, the induction motor (IM) and switched reluctance motor (SRM) have been applied. They are already employed in certain models of HEV/EVs. The properties required of the electrical steel sheet used in the motor core differ according to the motor type and design. Consider the working magnetic flux density, for example. In the case of magnet motors, they are almost always used with a flux density around 1T even when it is partly in the saturation region. On the other hand, the IM is operated with a higher flux density of about 1.5T so as to generate the induction current in the rotor secondary conductor, and the SRM uses a flux density in the near-saturated region (**Table 1**).

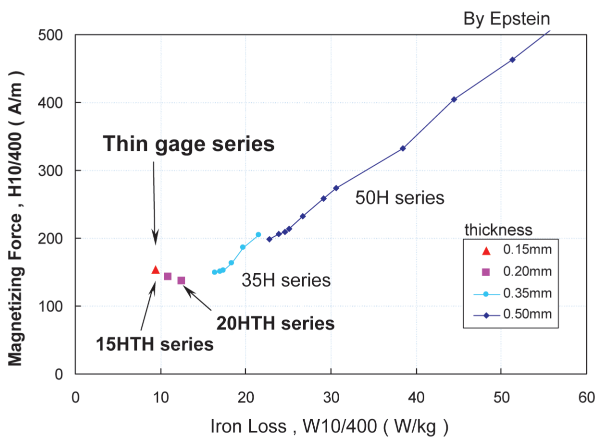


Fig. 3 Magnetic properties of thin gage series

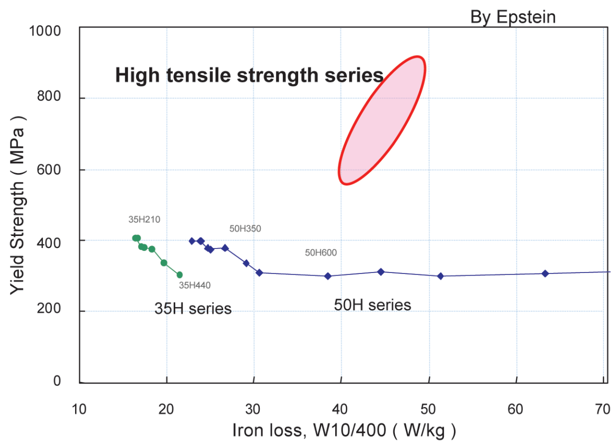


Fig. 4 Magnetic and mechanical properties of high tensile strength series

Table 1 Properties of several type motors for HEV/EV

			Torque	Field	Armature	Flux density
IM			Lorenz force	Stator windings	Eddy current	High (~ 1.5T)
DC BLM	SPM	Ferrite	Lorenz force	PM	Stator windings	Low (~ 0.8T) ↓ High (~ 1.2T)
	IPM		Lorenz force +			
		NdFeB	Reluctance torque			
SRM			Reluctance torque	Stator windings	–	High

Table 2 Material factors to affect magnetization process

Magnetization process	Material factors
Domain wall moving	Grain boundaries (grain size) Precipitations Defect, strain
Magnetization rotation	Grain orientation (texutre) Magnetic anisotropy constant
Magnetic saturation	Saturation magnetization

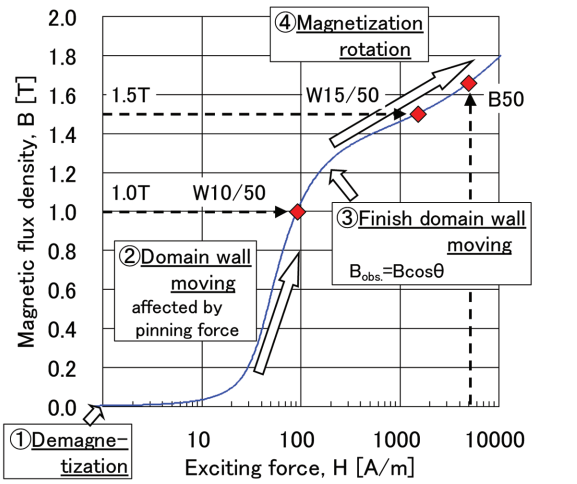


Fig. 5 Magnetization process of non-oriented electrical steel sheets

The magnetization process of the electrical steel sheet can be divided into (1) the magnetic domain wall motion in which the 180° magnetic domain wall near the external magnetic field begins to move and (2) the magnetization rotation in the direction of the external magnetic field which takes place after the completion of the domain wall motion. The above processes are influenced by different material factors. **Table 2** shows the magnetization processes and the material factors that influence them. Those factors affect the iron loss, specifically its hysteresis loss. The iron loss also includes the eddy current loss that is especially conspicuous at high frequencies. These losses need to be controlled by using the optimum working magnetic flux density and frequency (**Fig. 5**).

4. Magnetic Domain Structure of Non-Grain-Oriented Electrical Steel Sheet and Factors that Impede Magnetic Wall Motion

The grain-oriented electrical steel sheet has a grain size ranging from several to tens of millimeters. It shows a simple magnetic domain structure in which 180° domains are arranged in the rolling direction and the grains are strongly oriented toward {110}<001>. On the other hand, the non-grain-oriented electrical steel sheet has a grain size ranging from tens to hundreds of micrometers and shows a complicated magnetic domain structure because the grains are oriented in a relatively random manner. Depending on the grains, there are axes of easy magnetization in the direction perpendicular to the steel sheet. In addition, in the sheet thickness direction, there are several to tens of grains that differ in the magnetic domain structure. Their mutual influence results in a still more complicated magnetic domain structure.

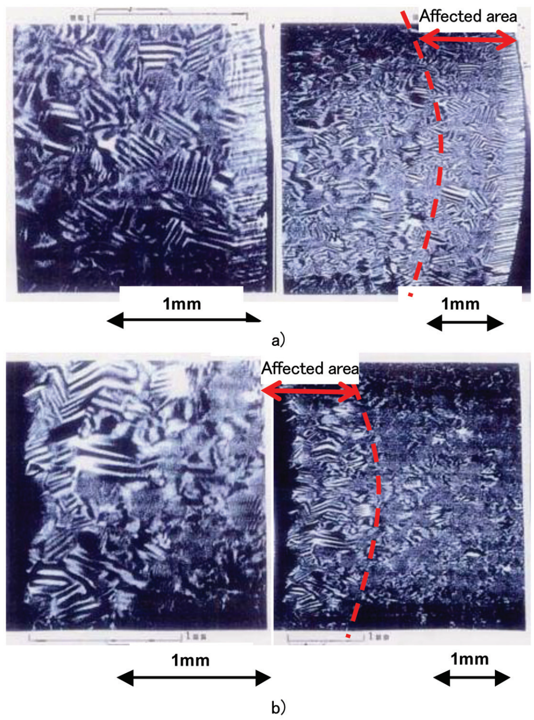


Fig. 6 Magnetic domain patterns of punched NO

Fig. 6 shows the magnetic domain structures of non-grain-oriented electrical steel sheet 50H290 observed from the surfaces when 22-mm-diameter disks were punched out from the steel sheet.[2] The figure shows the magnetic domain structures observed from the burred side (a) and those observed from the smooth radius side (b). The rolling direction and the direction of observation of the magnetic domains are right and left in the figure. The magnetic domain patterns in the work-affected regions (indicated by a broken line and an arrow in the figure) differ markedly from those of the unaffected region (away from the affected region). It can be seen that the width of the change in the affected regions is about three times the thickness of the steel sheet.

5. Effects of Strain/Stress in the Motor Manufacturing Process

The magnetic properties of electrical steel sheets are measured under the conditions specified by IEC 60404-2: "no stress," "uniform alternating field in specific direction," and "magnetic flux sine wave." In practice, however, the motor cores are used under conditions different from those mentioned above. Among the factors affecting the operating conditions of the cores are the strain of punching and the stress from fixing of the cores; the non-uniform magnetic flux attributed to the core construction; field rotation accompanying the rotor rotation; and distorted wave excitation caused by the presence of controlled harmonics and space harmonics. These factors cause an increase in iron loss.[3]

Of those, the strain and stress are inevitably introduced into the motor core manufacturing process (**Fig. 7**) contributing greatly to the increase in iron loss. **Fig. 8** shows an example of an evaluation of the iron loss of the stator cores using a rotational iron loss simulator.[1] The stator cores used were 120 mm OD, 24-slot ones prepared

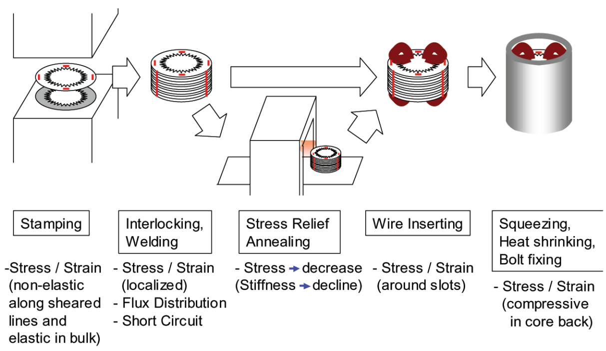


Fig. 7 Iron loss deterioration in motor manufacturing process

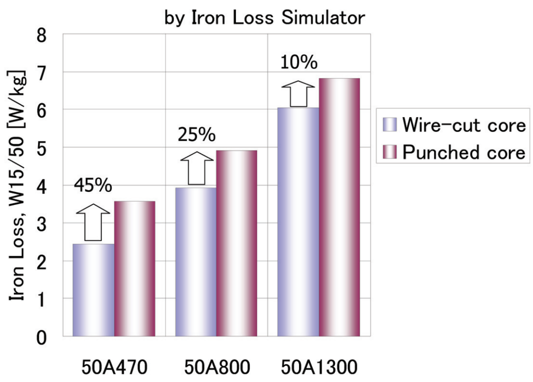


Fig. 8 Effect on iron loss of motor core manufacturing stress

by an electric discharge & punching process. The rotational iron loss simulator is a device Nippon Steel Corporation developed to directly evaluate the iron loss of a stack of several iron cores from a single iron core. It can be seen that although the increase in iron loss differs depending on the type of steel sheet, generally the iron loss increased as a result of the punching strain.

Fig. 9 shows the DC magnetization curves of a 3%Si non-grain-oriented electrical steel sheet cold-rolled to evaluate the deterioration of the magnetic properties of the electrical steel sheet caused by plastic strain.[4)] When a 2.7% plastic deformation was given to the steel sheet, the magnetization curve obtained before the cold rolling sharply decreased in gradient and the magnetic permeability μ (= B/H) decreased. As the amount of plastic deformation was increased from 2.7% to 19.6%, the magnetic permeability gradually decreased.

Fig. 10 shows the changes in the DC magnetization curve of a 3%Si non-grain-oriented electrical steel sheet when it was sheared in parallel with the rolling direction into two and four longitudinal sections. The magnetic permeability decreased and the magnetizing force required to secure a certain magnetic flux density increased, although the change in the DC magnetization curve is not as conspicuous as that caused by cold rolling. The region in which the magnetic permeability declined due to the shearing strain was estimated by using the magnetic permeability of the steel sheet subjected to 19.6% cold rolling that showed hardness comparable to that of the work hardening near the sheared edge of the steel sheet. In **Fig. 11** the result of the estimation obtained with the cold-rolled steel sheet is shown along with the results obtained with 0.2- and

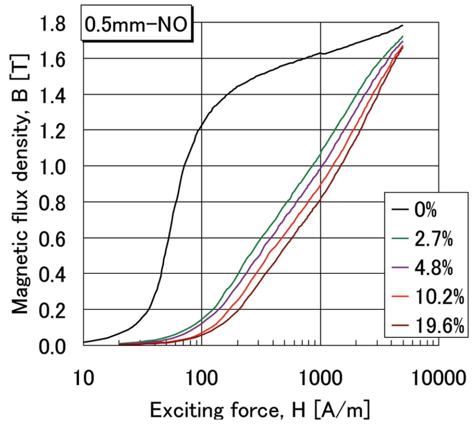


Fig. 9 Changes in magnetizing curve by plastic strain

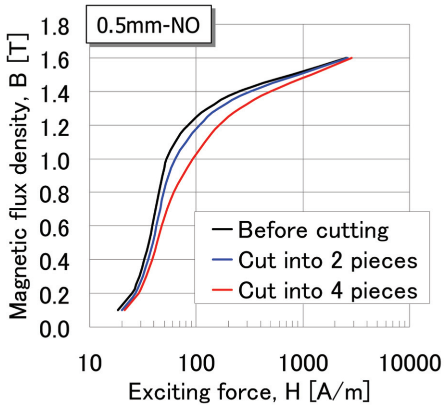


Fig. 10 Changes in magnetizing curve by shearing strain

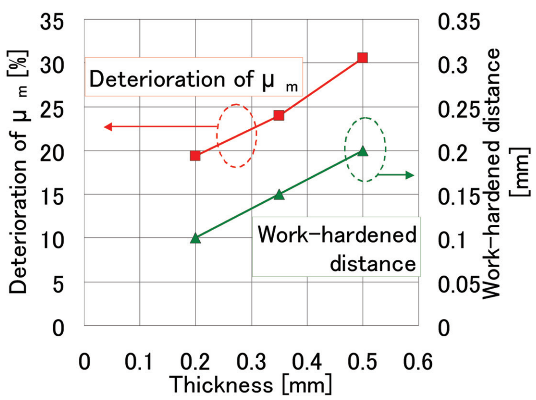


Fig. 11 Assumption of affected area by shearing

0.35-mm-thick 3%Si non-grain-oriented electrical steel sheets. The work-hardened region is about half of the sheet thickness and decreases in proportion to the sheet thickness. The work-affected region calculated from the overall decline in magnetic permeability also decreases in proportion to the sheet thickness but it is wider than the work-hardening region and several times greater than the sheet thickness. These results agree well with the results of the observations of the magnetic domains.

6. Analysis of Electromagnetic Fields Considering Strain, Stress, and Magnetic Anisotropy

In order to accurately evaluate the performance of a motor, it is necessary to consider the causes for the increase in iron loss described above. Numerical analysis or other appropriate techniques have recently been applied to optimize the core shapes and excitation conditions.

As an example, **Fig. 12** shows the results of a motor iron loss analysis that focused on the influences of magnetic anisotropy, strain, stress, and time harmonics.[5] Assuming that the difference between the iron losses obtained by the analysis with and without consideration given to the analysis conditions was 100% and looking at the increase in iron loss caused by each of the analysis items, we see that strain and stress have a significant influence. The non-grain-oriented electrical steel sheet shows much less magnetic anisotropy than the grain-oriented electrical steel sheet. Even so, with the manufacturing method used, a certain degree of magnetic anisotropy manifests itself.[6] For a segment core, it has been shown that the influence of magnetic anisotropy is strong because of the core construction[7]. Thus, it is possible to obtain highly accurate numerical analysis results by measuring the magnetic properties under stress/strain and at different angles.

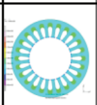
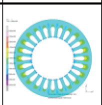
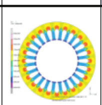
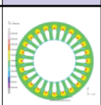
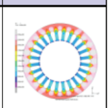
Analysis condition	Aniso-tropy	×	○	×	×	○
	Stress	×	×	○	×	○
	Har-monics	×	×	×	○	○
Iron loss contour maps						
Contribution			10%	50%	40%	100%

Fig. 12 Analysis for iron loss in motor core with various conditions

7. Conclusions

With the expanding market for HEV/EV and the increase in the number of HEV/EV models, traction motors for HEV/EV are becoming smaller in size, lighter in weight, and higher in efficiency. At the same time, new electrical steel sheets for the motor cores have been developed to meet the new requirements. The material factors that affect the magnetic properties of an electrical steel sheet differ according to the conditions under which it is used. Therefore, it is necessary to choose a suitable electrical steel sheet and pay due attention to the operation conditions of the traction motor. In addition, since the motor performance characteristics are influenced by the motor's operating conditions, it is important to evaluate the motor performance by numerical analysis taking into consideration the core construction, processing/fixing methods, motor control system, etc.

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