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Electrical Steel Sheet for Traction Motors of Hybrid/Electric Vehicles

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Abstract

Electrical steel sheet is used for core of traction motors of hybrid electric vehicles (HEV) and electric vehicles (EV), and affects performance of HEV/EV. In order to make motors to be small, light, powerful and efficient, there are many demands to electrical steel sheet. To realize these demands, development of electrical steel sheets with suitable qualities, and suitable application techniques of electrical steel sheet are required as well.

1. Introduction

Being environmentally friendly is one of the essential requirements for automobiles in the 21st century. Technologies were developed for a hybrid electric vehicle (hereinafter referred to as an HEV), which is driven by an internal combustion engine and an electric motor to improve fuel consumption and thus reduce the emission of exhaust gas, which is a principal cause of global warming. In 1997, the world's first mass production model of HEV was launched to the Japanese automobile market. The application of the HEV technologies has since expanded to other models. The response of an electric motor is better than that of an internal combustion engine, and its torque can be controlled more precisely. For these reasons, the application of HEV technologies is expected to expand to sport utility vehicles, for which excellent traction performance is required in addition to environmental considerations. Mass production of an HEV model was scheduled to begin in the U.S.A. in 2003, and the pragmatic HEV's initiated in Japan have become widespread around the globe. On the other hand, in December 2002, a fuel cell electric vehicle (FCEV), which does not emit harmful substances at all, was put to practical use in Japan for the first time in the world.

In an electric vehicle such as an HEV or FCEV, one or several electric motors (hereinafter referred to as an EV traction motor) constitutes the heat of its traction system, just as an internal combustion engine does in a conventional vehicle. An electrical steel sheet, which is the functional material of the iron core of the motor, is an essential material that influences traction performance and fuel consumption of an EV. This paper describes the latest electrical steel sheet products and related application techniques that support the performance enhancement of an EV traction motor.

2. Requirements for Electrical Steel Sheet for EV Traction Motor

The types of electric motor used as the EV traction motor are listed in **Table 1**[1,2). While each of the types has its advantages in different performance aspects, permanent magnet synchronous motors (PM motors) are used in all the HEVs that are currently being produced. The requirements for an electrical steel sheet are described hereinafter mainly in relation to the PM motor, but substantially the same requirements also apply to other types of motors.

Fig. 1 schematically illustrates the driving properties required of an EV traction motor, which are, in turn, reflected in the required properties of an electrical steel sheet used for the iron core of the motor. An EV traction motor has to have a high torque for starting, a high maximum revolution for maximum vehicle speed, and high efficiency in the most frequently used drive range for good fuel efficiency. In addition, since an EV traction motor is mounted in a limited space of a vehicle and is fed by a small battery, an EV traction motor is expected to have a compact design, light weight and high efficiency compared to the motors for other applications.

For raising motor torque, it is important not only to increase the drive current through the motor windings but also to increase the

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Table 1 Types of EV traction motor and their characteristics [1,2]

	Motor type	DC	Induction	Synchronous (PM)	Switched reluctance
Motor properties	Max. efficiency (%)	△ 85-89	○ 94-95	◎ 95-97	△○ <90
	Efficiency (load 10%) (%)	○ 80-87	○ 79-85	◎ 90-92	○ 78-86
	Max. revolution (rpm)	△ 4,000-6,000	◎ 9,000-15,000	○ 4,000-10,000	◎ <15,000
	Cost/ torque ($/kW)	○ 10	○ 8-12	△ 10-15	◎ 6-10
	Costs of controller	◎ 1	△ 3.5	○ 2.5	△ 4.5
	Rigidness	○ Good	◎ Best	○ Good	○ Good
	Reliability	△ Good	◎ Best	○ Good	○ Good

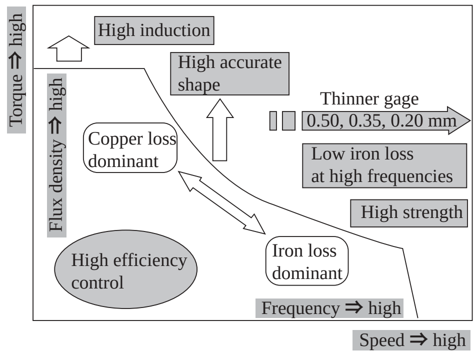

Fig. 1 Required performance of EV and requirements of electrical steel sheet for EV traction motor

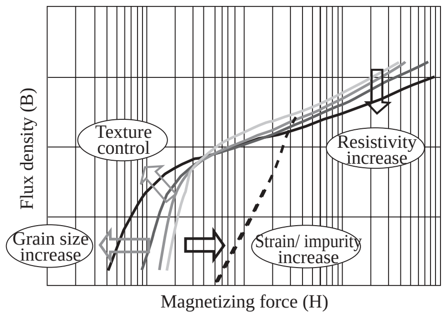

Fig. 2 Magnetizing characteristics of electrical steel sheet and principal influencing material properties

magnetic flux intersecting the windings. For this reason, the electrical steel sheet used for the motor is required to have higher magnetic flux density under given field strength, namely higher magnetic permeability. In addition, since it is effective for increasing magnetic flux density to minimize the gap between the rotor and stator, good stamping workability is required of an electrical steel sheet as well.

For compact design, a high maximum revolution is advantageous, but, since a high frequency excitation is required for this, the electrical steel sheet for the motor core must have low iron loss under high-frequency excitation. When the revolution of a rotor is high, the rotor is subjected to large centrifugal force, and the electrical steel sheet used for rotor must withstand the force. In the case of an IPM motor, in particular, in which permanent magnets are inserted in holes drilled through the rotor, ensuring the strength of the parts holding the magnets is essential.

Low iron loss and excellent magnetizing properties in the most frequently used drive range (intermediate flux density and frequency ranges) is important for reducing effective fuel consumption. In the case of an HEV, the motor runs idle without drive current while the vehicle is driven by the internal combustion engine, thus low iron loss is important for minimizing the power loss during the idle run.

3. Electrical Steel Sheet Suitable for EV Traction Motor

Besides an electrical steel sheet, sheets of a 6.5%Si steel, a Co-Fe alloy, a Ni-Fe alloy are also used as the materials for motor cores. However, few of them satisfy the characteristics required of an EV traction motor more economically and in a better-balanced manner than an electrical steel sheet does[3]. Therefore, a non-oriented electrical steel sheet (NO)[4] is actually used for the motor. A grain-oriented electrical steel sheet (GO)[5] may be used, but special measures have to be taken depending on the properties of the material.

Fig. 2 shows the principal characteristics of an NO steel sheet that influence its magnetizing properties. The magnetizing properties required for an EV traction motor are realized through measures such as the purification of steel and the control of alloying elements, grain orientation and grain size[5]. When an alloying element such as Si is increased, then electric resistance increases, the eddy current in a steel sheet is suppressed and as a result, iron loss is reduced[6], but saturation magnetic flux density is also reduced at the same time. It is necessary to control the iron loss and saturation magnetic flux density in a well-balanced manner. If strain or stress remains in a steel sheet, its magnetic domain structure becomes complicated and as a result, the magnetizing properties are deteriorated and iron loss is increased[6,7]. Thickness also influences iron loss significantly; the thinner a steel sheet is, the more eddy current is suppressed, and the less its iron loss becomes, but when the steel sheet is too thin, iron loss increases rather than decreases[8].

A new series of electrical steel sheet product has been developed to satisfy the requirements of an electrical steel sheet for an EV traction motor. **Fig. 3** shows the magnetic properties of the developed product series of high-efficiency electrical steel sheet, which has an improved magnetic flux density B50 (the flux density under a magnetizing force of 5,000 A/m), in comparison with those of conventional products (50H and 35H series). The new product series displays better B50 values at the same values of iron loss W10/400 (the iron loss under excitation of 1.0 T at 400 Hz), and it offers higher motor torque. **Fig. 4** shows the magnetic properties of a thin-gauge electrical steel sheet series for high-frequency use, which is designed to have low iron loss under high-frequency excitation. It is seen here that the thin-gauge product exhibits lower W10/400 values than those of conventional products 0.50 and 0.35 mm in thickness, while the deterioration of its magnetizing force H10/400 owing to its small thickness is inhibited . **Fig. 5** shows the magnetic properties of a high-strength electrical steel sheet series suitable for a high-speed rotor. Its strength is twice as high as those of conventional products or more, while the increase in the W10/400 value is suppressed.

4. Electrical Steel Sheet Utilization Technologies to

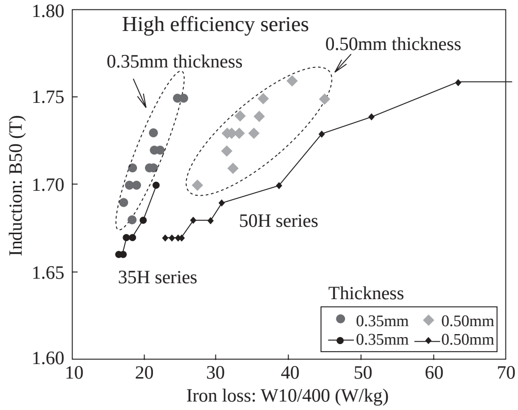

Fig. 3 Magnetic properties of high-efficiency electrical steel sheet

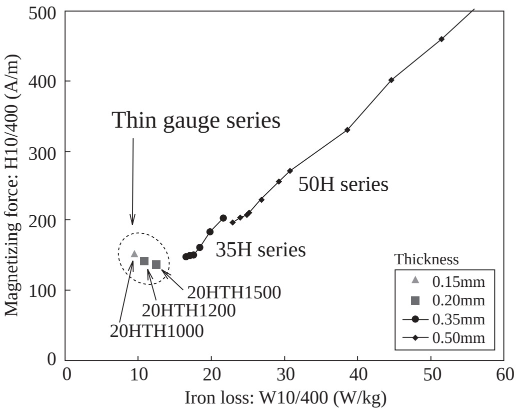

Fig. 4 Magnetic properties of HTH series thin-gauge electrical steel sheet for high-frequency use

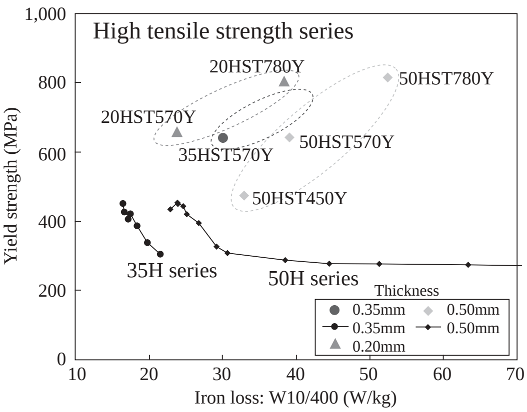

Fig. 5 Magnetic properties of HST series high-tension electrical steel sheet

Maximize Performance of EV Traction Motor

In accordance with the international standard measurement method IEC60404-2, the properties of an electrical steel sheet are measured under conditions of no stress, uniform alternating field in a prescribed direction, a sinusoidal flux wave form and so on. However, in reality, an iron core is used under conditions much different from the measurement conditions in the following aspects, as illustrated in **Fig. 6**:

(1) Magnetic flux is not uniform and its density shows certain unevenness for reasons of iron core structure and the non-linearity of its magnetizing properties.

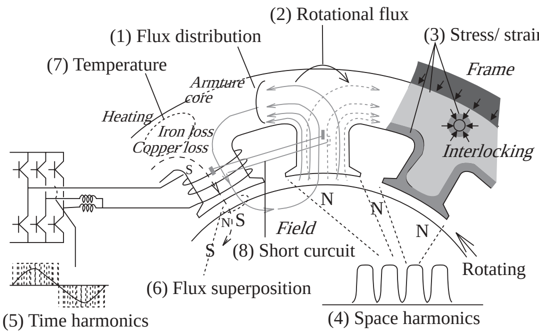

Fig. 6 Factors in real motor core to increase iron loss

(2) Magnetic flux rotates locally in an iron core as a result of the rotation of the rotor.

(3) Strain and stress remain in the steel sheets that form an iron core as a result of stamping work and interlocking to fix them together.

(4) There are space harmonics caused by the slots for windings between core teeth.

(5) There are time harmonics caused by the inverter circuits of a power source unit.

(6) There occurs the superposition of the field flux of a magnet and the magnetic field of the current through windings.

(7) Core temperature rises as a result of iron loss and copper loss, and temperature unevenness occurs depending on the method of cooling.

(8) Induction currents flow at parts where steel sheets touch each other at their edges or the surface where insulation is short-circuited as a result of the interlocking of a laminated core.

All these cause iron loss to increase[9]. If the iron loss increasing rate of a core is significant compared with that of electrical steel sheets, then there are cases where no improvement in the iron loss of a core is obtained no matter how low the iron loss of electrical steel sheets is.

Among the above iron loss increasing factors, the strain and stress mentioned in the above item (3) are introduced to the steel sheets mainly during the motor manufacturing processes, and their iron loss increasing effect is significant. **Fig. 7** schematically shows how the strain and stress are introduced during the processes. Non-elastic strain is introduced along the contour of core sheets during their stamping work. Besides, strain and stress are imposed locally when the stamped core sheets are laminated and put together to form a core by interlocking or welding. The strain and stress are mostly removed when the core undergoes stress relief annealing. Stress

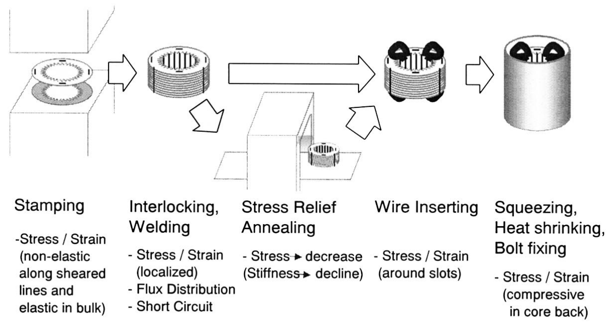

Fig. 7 Factors in core manufacturing processes to increase iron loss

may be imposed also during the wire insertion work. If a core is fitted into a motor case by press fitting or heat shrinkage fitting, then a large compressive stress remains in the entire core.

Fig. 8 comprises a sectional micrograph of a stamped edge and a numerically simulated strain distribution of the portion. An intensive compressive strain is imposed on the portion of the steel sheet along the stamped edge to a distance nearly equal to its thickness from the edge, and a tensile stress matching the compressive strain is imposed to the other portion of the steel sheet[10]. The authors analyzed the effects of the residual strain introduced by the stamping work upon the iron loss using the rotating iron loss simulator described later, and the results are shown in **Fig. 9**. The iron loss of a core formed by stamping work was found larger than that of a core of the same shape formed by wire cutting, which caused only a negligible work strain, but the iron loss was reduced through stress relief annealing to a level equal to or lower than that of the core formed by wire cutting. The annealing relieved strain and in the case of low-grade materials (50H800 and 50H1300), crystal grains grew and their iron loss decreased to lower than that of the core formed by wire cutting. The rate of the iron loss increase caused by stamping work was larger with the high-grade material (50H470) than with the low-grade ones.

Fig. 10 shows the influence of elastic stress over the iron loss of electrical steel sheets. Iron loss increases significantly under a compressive stress, and the rate of the iron loss increase becomes larger as the magnetic flux density is lowered. It is presumed from this that the increase in the iron loss of a real core is significant when there is residual compressive stress as a result of press fitting or heat shrinkage fitting. In addition, it has been made clear that the iron loss increase resulting from the inter-laminar short-circuiting of the above item (8) is significant when the position of interlocking is inappropriate[11].

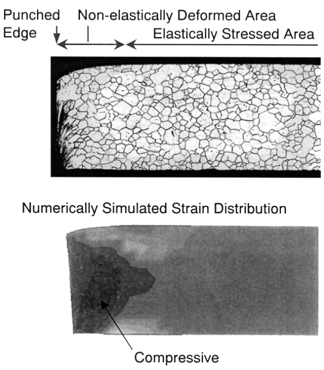

Fig. 8 Sectional micrograph of stamped edge and numerically simulated strain distribution

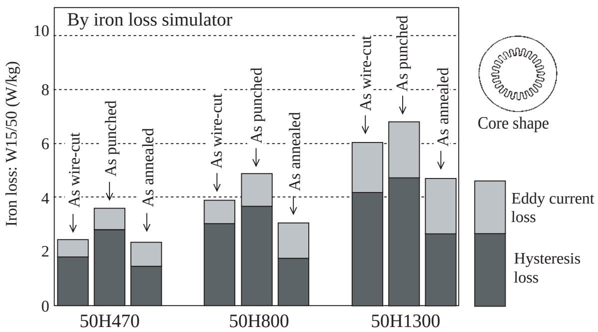

Fig. 9 Influence of residual strain resulting from stamping work over iron loss

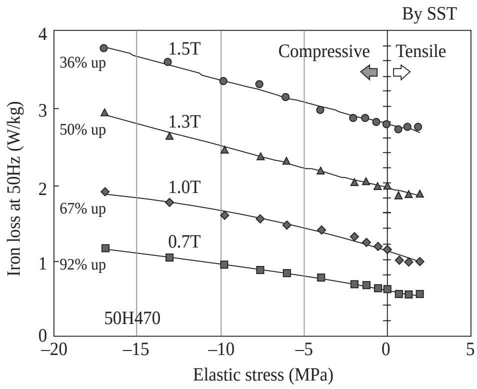

Fig. 10 Influence of elastic stress over iron loss of electrical steel sheet

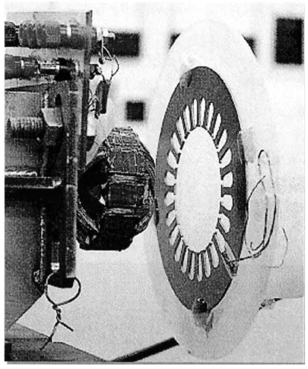

Fig. 11 Rotating iron loss simulator

In the latest motor design, the shape and magnetizing conditions of a core are optimized using numerical analyses and other assisting methods. For accurately estimating core performance, it is necessary to take into consideration the influencing factors of a real core such as those shown in Fig. 6. Further, since the magnetic properties of an electrical steel sheet have non-linearity, it is necessary for a motor designer to obtain the numerical database of the magnetic properties of an electrical steel sheet from its producer in order to reflect in motor design the behaviors of the magnetic properties under stress. For enhancing the accuracy of numerical calculations, in addition, it is necessary to evaluate the iron loss of a core in a manner to allow a direct comparison with a calculation result. **Fig. 11** shows the rotating iron loss simulator that Nippon Steel developed for directly evaluating the iron loss of a real core[12]. The simulator is capable of measuring the iron loss of a core composed of only one steel sheet or several sheets, and, as such, constitutes an evaluation means for improving the performance of a motor at its design stage.

5. Closing Remarks

A compact design, light weight and high performance motor is expected from an EV traction motor and in this relation, excellent characteristics are required in varied aspects toward an electrical steel sheet that is used as the material of a motor core. In response to the requirements, series of new electrical steel sheet products have been developed. It is important not only to select the type of electrical steel sheet most suitable for the design of an EV traction motor, its fabrication processes and the drive range of an EV, but also to employ the utilization technologies that maximize the properties of an electrical steel sheet in a real core.

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