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Electrical Steels for EV Traction Motors in JFE Steel

1. Introduction

Electrical steels are used as core materials for electric vehicle (EV) traction motors, and are the key material which affects motor performance.

JFE Steel offers a lineup of electrical steels for EV traction motors that includes the JNE™ Series, JNEH™ Series, JNP™ Series and JNT™ Series, and has also expanded its lineup of high Si steel sheets for high speed EV traction motors. This article introduces these electrical steels for EV traction motors.

2. Properties Required in Materials for EV Traction Motors

Various properties are required in electrical steels used as core materials for EV traction motors. Since high torque is necessary when a vehicle starts and accelerates, high magnetic flux density in a high magnetic field is required in electrical steel sheets. On the other hand, because iron loss accounts for a large percentage of motor loss in the high rotational speed range, a material with low high frequency iron loss is required, and high thermal conductivity is also necessary to reduce the generated heat. In interior permanent magnet (IPM) motors, high strength and high fatigue strength are demanded in electrical steel sheets to prevent scattering of the magnet. Although these various properties are required in electrical steel sheets, it is difficult to satisfy all these requirements with one type of electrical steel. Therefore, each type of electrical steel is used appropriately corresponding to the level of performance required in the motor.

3. Electrical Steels for EV Traction Motors

3.1 Electrical Steel Sheets for Energy Efficient Motors: "JNE™"

Because increasing specific resistance by Si addition is effective for reducing iron loss in electrical steels, approximately 3 mass% Si is added to high grade electrical steels. On the other hand, since Si is a non-magnetic element, increased addition of Si reduces saturation magnetization. For this reason, it was difficult to produce high magnetic flux density-low iron loss materials by the conventional technique of Si addition. To solve this problem, JFE Steel attempted to optimize the amounts of added alloy elements such as Si, Al, etc. and the grain diameter, increase the favorable texture for magnetic properties, and reduce impurities in the steel[1, 2]. **Figure 1** shows the properties of the JNE Series, which was developed by using a combination of these technologies[3]. The JNE Series has an excellent balance between magnetic flux density and iron loss in comparison with the conventional JN Series, and can make a large contribution to high energy efficiency and high torque in motors.

3.2 Thin Gauge Electrical Steel Sheets for High Frequency Motors: "JNEH™"

Against the background of higher motor speeds accompanying more compact EV traction motors, strong demand for reduction of high frequency iron loss in electrical steel sheets is expected in the future. Because eddy current loss is the controlling factor for iron loss in the high frequency range and is proportional to the square of sheet thickness, reducing the sheet thickness is effective for reducing iron loss. Therefore, the development of thin gauge electrical steel sheets has been promoted from this viewpoint[4].

Figure 2 shows an example of the magnetic properties of thin gauge electrical steel sheets with thicknesses of 0.20, 0.25 and 0.30 mm[3]. In comparison with the highest grade material with a thickness of 0.35 mm, iron loss decreases by about 25 to 30 % in the thin gauge electrical steel sheet with a thickness of 0.20 mm, and this tendency becomes even more remarkable as the frequency increases.

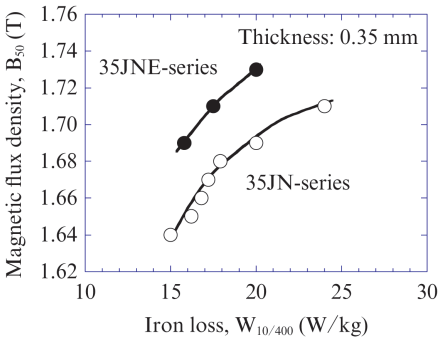

Fig. 1 Magnetic properties of non-oriented electrical steel sheets for energy efficient motor

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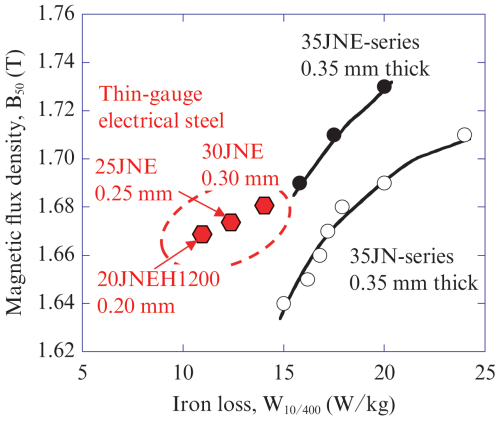

Fig. 2 Magnetic properties of thin-gauge electrical steel sheets

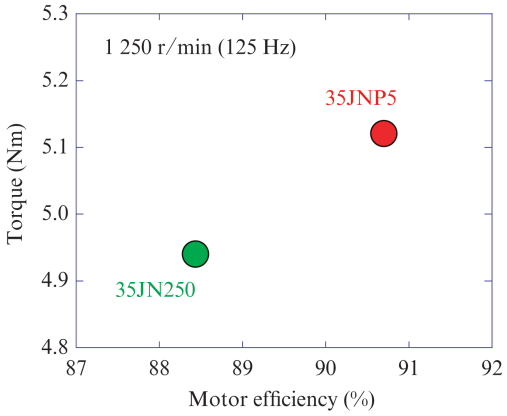

Fig. 4 Motor properties of direct drive motor

3.3 Electrical Steel Sheets for High Torque Motors: "JNP™"

Large torque is required in EV traction motors when starting, hill climbing and accelerating, and for this reason, further increases in magnetic flux density are desired in electrical steel sheets used as core materials. Against this backdrop, JFE Steel developed the JNP Series, which offers higher magnetic flux density than the conventional material[5]. **Figure 3** shows the balance between magnetic flux density and iron loss of the developed materials. In comparison with the JNE Series, the magnetic flux density of the JNP Series is approximately 0.01 to 0.02 T higher at the same iron loss. Aiming at high magnetic flux density by texture control, in the JNP Series, the amounts of added Si, Al, Mn and other alloy elements are optimized, grain boundary segregation elements are used, and optimization technologies are applied in the intermediate processes.

Because this material has high magnetic flux density, it is considered suitable for motors requiring high torque. Direct-drive in-wheel motors are a type of EV motor in which high torque is required[6]. High torque is demanded in direct-drive motors in order to rotate the wheel directly without reduction gears. In comparison with motors that use gears for high speed rotation, one distinctive characteristic of direct-drive motors is a low ratio of iron loss to total motor loss due to their low rotational speed. Based on this, the iron loss requirement for electrical steel sheets for direct-drive motors is not particularly high, but on the other hand, high magnetic flux density is strongly required.

Figure 4 shows the motor efficiency and torque of an IPM type direct-drive motor with a rated output of 1.6 kW at a rotational speed of 1 250 rpm (equivalent to a vehicle speed of 60 km/h). In comparison with the 35JN250 used as the conventional material, both torque and efficiency are improved by using the developed 35JNP5. Thus, 35JNP5 is a suitable core material for high torque motors such as direct-drive motors.

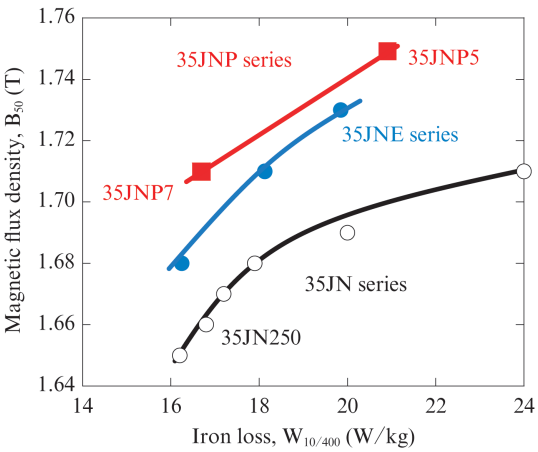

Fig. 3 Magnetic properties of JNP™ series

3.4 High Strength Electrical Steel Sheet for Rotors: "JNT™"

In the rotors of IPM motors, large stress is applied to the bridge structure by the centrifugal force of the magnet during high speed rotation. From the viewpoint of rotor strength, it is possible to expand the width of the bridge, but because expanding the bridge width increases leakage flux of the permanent magnet, which reduces motor efficiency, the width of the bridge structure is designed to be as narrow as possible within the range that satisfies rotor strength. Therefore, sufficient yield strength to withstand the centrifugal force during high speed rotation and fatigue strength under cyclic loading are necessary in the electrical steel sheets used as rotor materials [7]. Particularly in motors with concentrated windings, it is also necessary to reduce high frequency iron loss, because iron loss caused by higher harmonics occurs at the rotor surface.

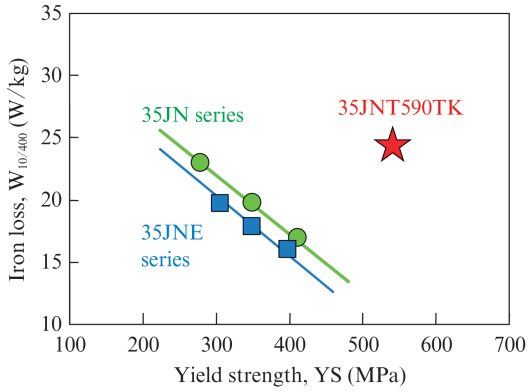

Fig. 5 Magnetic and mechanical properties of high-strength electrical steel sheet

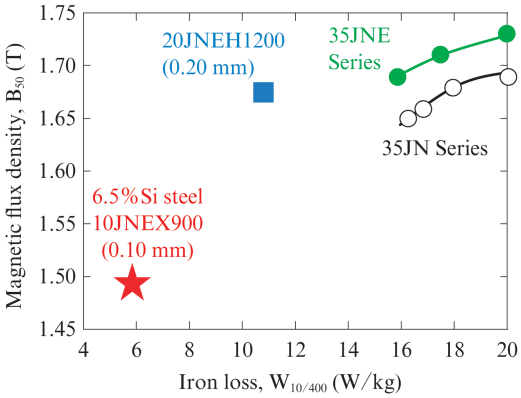

Fig. 6 Magnetic properties of 6.5%Si steel sheet

JFE Steel developed 35JNT590TK as this type of high strength electrical steel sheet for rotors. **Figure 5** shows the properties of this high strength electrical steel sheet. High strength technologies such as solid solution strengthening and grain refining are applied in this material, achieving a strength increase of approximately 30 % in comparison with the conventional materials.

Use of this electrical steel sheet as a rotor material can contribute to downsizing of EV traction motors, an increase in the maximum rotational speed, and high energy efficiency by suppressing leakage flux by adoption of a narrow bridge structure.

3.5 6.5 % Si Steel Sheet: "JNEX™"

6.5 % Si steel has been known since the 1950s[8], and it had become clear that substantially zero magnetostriction and the highest values for magnetic permeability and iron loss can be achieved by adding 6.5 mass% Si to steel. However, if the Si content is increased, elongation of the material decreases sharply, and production of thin gauge electrical steel sheets by rolling becomes impossible. For this reason, Si addition had been limited to around 3 mass% in the highest grade conventional electrical steel sheets. In recent years, however, a production technology for high Si steel sheets utilizing CVD (chemical vapor deposition) was developed as an alternative to rolling, and mass production of 6.5 % Si steel sheets became possible[9].

Figure 6 shows the magnetic properties of JFE Steel's 6.5 % Si steel sheet (JNEX™). The iron loss of the 6.5 % Si steel sheet is remarkably low in comparison with the conventional non-oriented electrical steel sheets. Therefore, excellent properties can be expected in this 6.5 % Si steel sheet as a core material for high speed motors[10].

3.6 Si Gradient Steel Sheets: "JNHF™, JNRF™"

Si gradient steel sheets (JNHF™ Series) with a Si concentration gradient in the sheet thickness direction have also been developed for use in high speed motors by using the above-mentioned CVD process[11, 12]. The JNHF Series not only possesses iron loss properties surpassing those of JNEX in the high frequency range of 10 kHz and higher, but also has the merits of high magnetic flux density and excellent formability by punching, etc. owing to its low Si content in the sheet center-of-thickness area in comparison with JNEX.

Although the JNEX Series and JNHF Series have excellent high frequency iron loss, and thereby contribute to high energy efficiency in EV traction motors, their magnetic flux density is low compared to that of general non-oriented electrical steel sheets, and decreased motor torque was a problem. To overcome this issue, JFE Steel developed the JNRF™ Series with improved magnetic flux density, while using the eddy current loss reduction technology by applying a Si gradient in the sheet thickness direction. **Figure 7** shows the magnetic properties of the JNRF Series. In

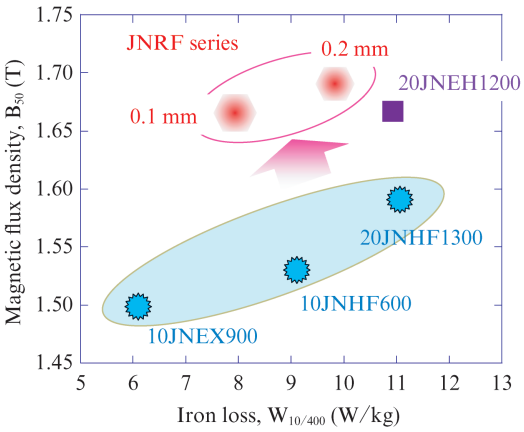

Fig. 7 Magnetic properties of Si gradient steel sheets

comparison with the JNHF Series, the JNRF Series has low iron loss at 400 Hz, which is equivalent to the operating frequency of EV traction motors, and also shows a large improvement in magnetic flux density. Thus, this product can contribute to high torque in combination with high energy efficiency in EV traction motors.

4. Conclusion

This article introduced the properties of electrical steel sheets used as core materials of EV traction motors. With further expansion of the EV market forecast in the future, it is thought that even higher efficiency and higher output will be required in traction motors. Although customers' requirements for electrical steel sheets used as core materials are also expected to become both more advanced and more diverse, JFE Steel will continue to contribute to higher performance in EV traction motors through the development of new materials that respond to those requirements.

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