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Insulated Pure Iron Powder for Soft Magnetic Composite Core (Denjiro™)

1. Introduction

In the midst of the rapid transition from fossil fuels to renewable energy and vehicle electrification, power electronics, which efficiently control electrical power through semiconductor switching, can be considered a key technology for achieving a carbon-neutral society. Increasing the switching frequency is generally advantageous for downsizing power electronic devices. In the past, the operating frequency of high-capacity power supplies was limited to a few 100 Hz due to semiconductor constraints. However, semiconductors have become more advanced, and relatively large-capacity power electronic devices, such as power conditioners for photovoltaics and inverters for electric vehicles, are now beginning to be operated at frequencies ranging from a few kHz to several 10 s of kHz. In order to further downsize these devices, magnetic core materials with high saturation flux density and low iron loss at high frequencies are required for the motor and reactor components used in these devices.

The electrical steel sheets currently produced by JFE Steel are widely used as stacked cores (or toroidal cores) for industrial equipment motors and power distribution transformers, primarily in the frequency range of several 100 Hz or lower. The high-silicon content electrical steel sheets produced by JFE's proprietary CVD process are used as magnetic cores for electrical devices that prioritize low noise and high efficiency, particularly in the frequency range of several 100 Hz to several 10 s of kHz. Furthermore, the MnZn ferrite cores produced by JFE Chemical are primarily used as sintered cores for transformers and inductors in the frequency range exceeding 100 kHz in electronic devices[1)].

On the other hand, when considering power electronic devices operated at frequencies ranging from a few kHz to several 10 s of kHz, the use of electrical steel sheets raises concerns about heat generation in magnetic cores due to significant eddy current loss. While high-silicon electrical steel sheets are one of the candidate materials, their application is primarily targeted toward high-value-added sectors due to the nature of the manufacturing process. MnZn ferrite cores exhibit low high-frequency loss and are suitable for mass production, but their lower saturation flux density requires larger-sized magnetic cores.

Soft magnetic composite (SMC) cores, which consist of insulated pure iron powder, offer promising candidate materials for power electronic devices. These cores have higher saturation flux density compared to ferrite cores and lower eddy current loss compared to electrical steel sheets, and can also be mass-produced relatively easily. Therefore, JFE Steel applied its water atomization technology to the development of an insulated pure iron powder trade-named Denjiro™. In this article, we will introduce the main characteristics of Denjiro, evaluate its iron loss under inverter excitation, and present an example of a prototype and evaluation of an axial gap motor under specific conditions.

2. Characteristics of Insulated Pure Iron Powder (Denjiro™)

Denjiro™ was developed to reduce hysteresis loss in magnetic cores from the perspective of particle design[2)], such as spheroidization of particles and coarsening of crystal grains by minimizing impurities. **Photo 1** shows the appearance of Denjiro and its typical particle morphology. If particle sphericity is poor, strain is easily introduced during powder compaction, leading to an increase in hysteresis loss. Therefore, the water atomization conditions when manufacturing Denjiro are optimized to enhance particle sphericity in comparison with the conventional iron powders used in powder metallurgy. The average particle size is set to be below 100 μm to reduce eddy current loss, and an insu-

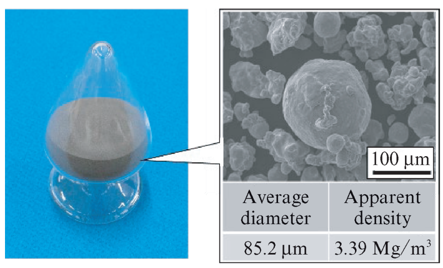

Photo 1 Insulated pure iron powder (Denjiro) and typical particle morphology

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lation coating is applied by a solvent-free treatment method to reduce its environmental impact.

The magnetic properties of the SMC core were evaluated using a ring sample (outer diameter: 38 mm, inner diameter: 25 mm, thickness: 6.0 mm, density: 7.60 $Mg{\cdot}m^{-3}$), which was compacted at 980 MPa and heat treated in a nitrogen atmosphere at 600°C.

Figure 1 shows the DC magnetization curve of Denjiro. It can be observed that Denjiro exhibits a relatively large slope in the region where the magnetic flux density B exceeds 1.6 T. This suggests that Denjiro can be expected to be effective in downsizing of DC reactors that require large inductance even in high current ranges.

Figure 2 presents the characteristics of iron loss measured under sinusoidal excitation conditions conforming to JIS standards. A Steinmetz-type regression equation of $W = 0.0415B^{1.75} f^{1.13}$ was derived from the measured data. Here, W ($W{\cdot}kg^{-1}$) represents the iron loss of the material, B (T) denotes the excitation magnetic flux density, and f (Hz) is the excitation frequency.

Table 1 presents a iron loss comparison of Denjiro and an electrical steel sheet (35JN360) with a thickness of 0.35 mm, which were evaluated under the same conditions. Denjiro exhibits lower iron loss on the high-frequency side beyond 1 kHz. This is attributed to the lower eddy current loss of the SMC core compared to the electrical steel sheet, which helps suppress the increase in iron loss at high frequencies. Thus, Denjiro can be considered a promising magnetic core material for high-frequency applications above several kHz.

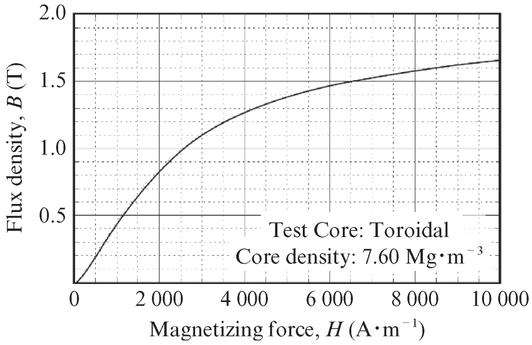

Fig. 1 D.C. magnetization curve of Denjiro™

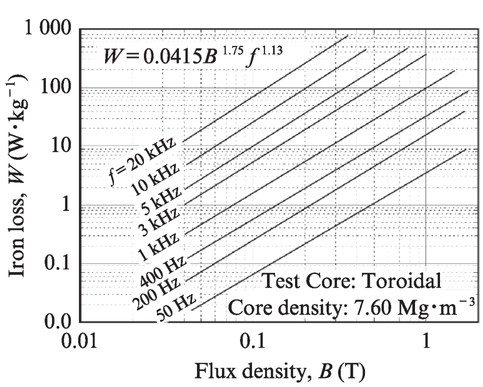

Fig. 2 High-frequency iron loss curves of Denjiro™

Table 1 Iron loss comparison of Denjiro™ and electrical steel sheet

	Iron loss ($W{\cdot}kg^{-1}$)				
	$W_{10/50}$	$W_{10/400}$	$W_{10/1\,k}$	$W_{2/5\,k}$	$W_{1/10\,k}$
Denjiro™ (SMC core)	3.7	32	90	41	28
Electrical steel sheet: 35JN360	1.3	20	80	51	42

SMC: Soft magnetic composite

Furthermore, Denjiro can be processed into SMC cores with near-net shapes, and it possesses the unique feature of three-dimensional isotropic magnetic properties[2)]. This makes it suitable for small magnetic cores with complex shapes that are difficult to achieve with electrical steel sheets.

3. Evaluation of Iron Loss under Inverter Excitation

Currently, many high-efficiency motors are driven by PWM (Pulse Width Modulation) inverter systems, which control the AC output by modulating the pulse width of a constant voltage. In the conventional motor design process, the iron loss data of magnetic materials measured under sinusoidal excitation have been used. However, the actual inverter output is not a simple sinusoidal AC waveform, but contains harmonic components caused by semiconductor switching, and the increase in iron loss due to these high-frequency components cannot be ignored. In order to improve design accuracy, evaluations of inverter-excited iron loss have also been conducted in recent years, specifying the carrier frequency fc and the modulation rate m of the PWM control factor[4)].

Figure 3 shows the results of iron loss evaluations under both sinusoidal excitation and PWM inverter excitation with SiC devices (carrier frequency fc = 5 kHz, modulation rate m = 0.4). The two excitation tests were performed under the same AC conditions (magnetic flux density B = 1.0 T, frequency f = 400 Hz). Under sinusoidal excitation, as mentioned in the previous section, the electrical steel sheet has lower iron loss compared to Denjiro™. However, under inverter excitation, Denjiro exhibits lower iron loss than the electrical steel sheet because the eddy current loss in Denjiro is lower than that in the electrical steel sheet and the increase in iron loss due to the high-frequency components of the inverter is suppressed[3)]. Considering application under inverter excitation, Denjiro can be considered a promising candidate for mag-

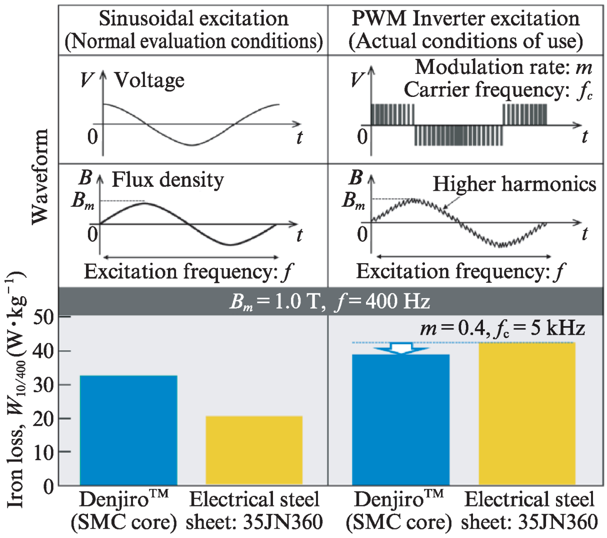

Fig. 3 Comparison of iron loss under sinusoidal and inverter excitation

netic core materials even under AC conditions with frequencies below 1 kHz.

Currently, JFE Steel is also considering a method for accurately converting iron loss values under sinusoidal excitation to them under inverter excitation by using the values of the PWM carrier frequency and modulation rate.

4. Example of Prototype and Evaluation of an Axial Gap Motor

Figure 4 shows a comparison of the general configuration of a radial gap motor, which is rotated by radial magnetic force, and an axial gap motor, which is rotated by axial magnetic force. Structurally, the axial gap motor is known to be capable of obtaining higher torque and is advantageous for motor downsizing. However, because a three-dimensional magnetic core design is required, it is difficult to apply stacked cores made of electrical steel sheets, so there are currently few practical examples. In contrast, Denjiro™ can easily be applied to small and complex-shaped magnetic cores through powder compaction, and the obtained magnetic properties of the cores are isotropic. Therefore, Denjiro is expected to be a suitable magnetic core material for axial gap motors[2].

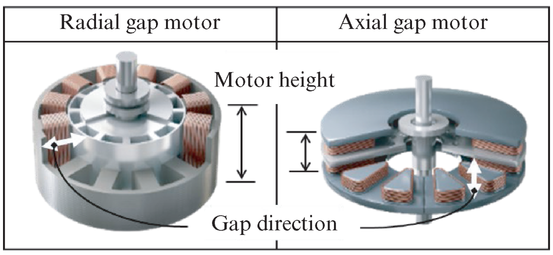

Fig. 4 Comparison of motor structures

To quantify the benefits of using Denjiro, an analysis was conducted using an electric air-conditioner compressor obtained from a commercially-available electric vehicle (radial gap motor using 0.35 mm thick electrical steel sheets produced by another maker) as the model motor. A prototype of an axial gap motor was fabricated using Denjiro so as to achieve equivalent efficiency and torque. The basic specification is shown in **Table 2**. In this case, the structure of the axial gap motor was a single rotor/double stator type with 14 poles and 24 slots.

Photo 2 shows an overview of the motor prototyping process. Although stator cores are normally processed to near-net shape by powder compaction, in this prototype, a 1 000-ton press machine was used for powder compaction at a surface pressure of 980 MPa. A large tablet with dimensions of Φ110 mm × 30 mm (density: 7.60 Mg·m^{-3}) was fabricated, and the tablet was then machined to the desired shape. The design and assembly of the motor, as well as the fabrication of the rotor including the permanent magnets, were carried out with the assistance of a start-up company originating from a university.

Table 3 presents the evaluation results of the motor prototype using Denjiro, along with the model motor analysis values and the design values of the axial gap motor. Compared to the radial gap model motor, the axial gap motor used in this evaluation was designed by electromagnetic field analysis to achieve a 48% reduc-

Table 2 Specifications of prototype motor

Item	Specification
Driving	AC Synchronous
Configuration	Single rotor/Double stator, SPM
Number of slots/poles	24 (12×2)/14
Winding method	Concentrated winding
Max. efficiency	>92%
Max. torque	>4.5 N·m
Max. speed	~7 000 rpm

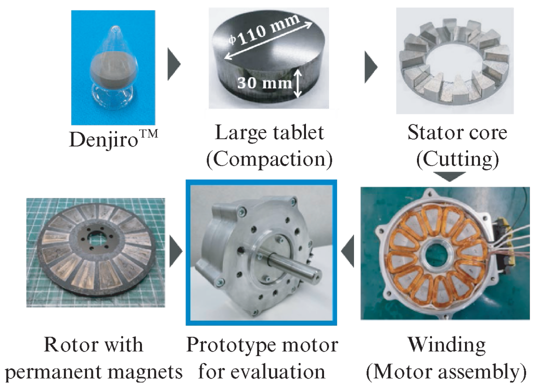

Photo 2 Manufacturing process of axial gap motor

Table 3 Evaluation result of prototype motor

Item	Model motor (Radial gap)		Prototype motor (Axial gap)	
	Analysis		Design	Measurement
Core diameter (mm)	90		110	
Core weight (g)	1 270	Downsizing	760 (40%↓)	
Motor height (mm)	62		32 (48%↓)	
Max. efficiency %	92-94	Equivalent	94	93
Max. torque (N·m)	4.4		5.2	5.4

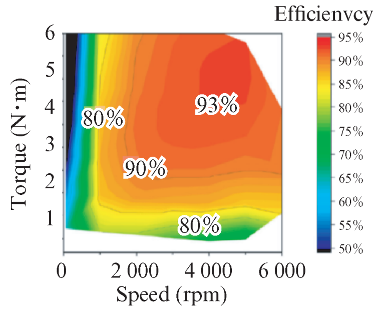

Fig. 5 Efficiency map of the prototype motor (measurement)

tion in axial length and a 40% reduction in weight. The actual measurements of the prototype motor confirmed that it exhibited performance almost equivalent to the model motor, as predicted by the design. The results showed a maximum efficiency of 93% and a maximum torque of 5.4 N·m.

Figure 5 shows the measurement results of the efficiency map for rotational speed and torque. The motors were operated under various conditions, and it can be seen that the prototype motor exhibits high efficiency over a relatively wide range of operating conditions.

There are various challenges to the widespread use of axial gap motors, such as simplifying the motor design, improving dimensional and assembly accuracy, and establishing mass production systems. However, these results demonstrate that Denjiro can significantly contribute to downsizing and improvement of the efficiency of conventional motors.

5. Conclusion

In conclusion, this paper has introduced a prototype evaluation of an axial gap motor as an example of an application of Denjiro™. However, expansion of its applications to other magnetic components is also expected. We plan to provide our customers with not only products and information on fundamental characteristics, but also new material development and timely solution proposals through technical exchange, including evaluations considering actual use conditions, supply of the large tablet shown in Photo 2, and motor prototype evaluations.

References

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