Thin and High-Torque Axial Gap Motor Using Soft Magnetic Powder Cores

Asako WATANABE*, Tatsuya SAITO, Tomoyuki UENO, Hijiri TSURUTA, and Yuichi NAKAMURA

Axial gap motors have been attracting attention as demand increases for thinner motors with a higher output. However, radial motors using laminated steel sheets remain dominant in the market, and the use of axial gap motors is still limited due to the difficulty in producing three-dimensional magnetic cores with laminated steel sheets. We have built an axial gap motor using soft magnetic powder cores that feature magnetic isotropy and high design flexibility. The motor offers high torque and cost efficiency compared with a conventional radial motor of the same size.

Keywords: soft magnetic powder core, motor, axial gap, thin, high torque

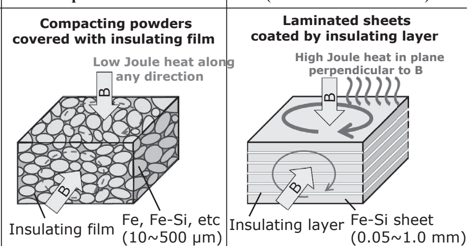
1. Introduction

Due to a rise in the number of electric vehicles, performance advancement in electric appliances, and the automation of factory work, motors that are the driving parts of these products and systems have been playing an increasingly important role. The number of motors installed in vehicles is also increasing, mainly due to the growing popularity of electric vehicles, but also because of the conversion to electronic parts in gasoline-engine vehicles. For example, cooling water pumps and cooling air fans are equipped with auto start/stop systems to keep the engine temperature low while the engine is not running. Not only the number of motors but also that of vehicle components in general is rising. This makes the space available for actual motors increasingly small. One of the most effective solutions is to decrease the motor's profile. However, the currently most common motor is a radial gap motor (RGM), and if an RGM is made thinner, its torque is reduced. To work on this problem, an axial gap motor (AGM) has come into focus as it is thin and delivers high torque. A motor consists of a soft magnetic core, magnets, copper wire, and bearings. For an AGM, the soft magnetic core needs to be designed with a three-dimensional approach. Magnetic steel sheets*[1] have been traditionally used to produce the motor core; however, it is difficult to produce an AGM core using magnetic steel sheets. This is why the commercial adoption of AGMs has been limited. To address this issue, Sumitomo Electric Industries, Ltd. has created an AGM adopting a soft magnetic powder core (SMPC), which is easily shaped and isotopically magnetized compared with magnetic steel sheets. In tests, a thin AGM prototype with an SMPC demonstrated higher torque and higher efficiency compared with an RGM. This paper describes the features of the SMPC and performance assessment of the AGM prototype with the SMPC. We also introduce our development efforts for new components and technologies.

2. Overview of the Soft Magnetic Powder Core

The SMPC is made by compacting soft-magnetic powder coated with a very thin insulation film. Pure iron powder and ferrous alloy powder are suitable for producing soft-magnetic powder as they show high saturation flux density*[2] and high plastic deformation capacity when compacted. Compacting this powder, in which each particle is insulated, to a high density creates an excellent soft magnetism, providing both high flux density and high electrical resistance at the same time. Table 1 shows the features of an SMPC compared to a core made of magnetic steel sheets. Unlike the magnetic core made of magnetic steel sheets, the core made of soft magnetic powder is magnetically isotropic and, therefore, magnetic paths can be formed in any directions. Also, usage of powder enables net-shape production*[3] of the core through powder injection into a variety of mold shapes. With this method, the core can be shaped with a great freedom compared with when using magnetic steel sheets, making it suitable to create the wider shape of core needed for an AGM. The Japanese Industrial Standards (JIS) define magnetic properties for magnetic steel sheets. However, measurements are taken for an individual sheet before it is layered, and it is

Table 1. Feature of soft magnetic powder core

	Soft magnetic powder core	Magnetic steel sheets (conventional material)
Schematic illustrations		
Magnetic isotropy	good	poor
Shaping flexibility	good	okay
Performance in product	good	okay/poor
AC-magnetic propertiy	good	okay

known that there are gaps between the design values and actual measurements of motor performance.[1],[2] This is because the magnetic properties deteriorate due to the deformation caused by stress and thermal warping that occur in press-cutting, caulking, and welding. On the other hand, the magnetic properties of an SMPC are measured with a test piece created using the same compaction method as the final product. Thus, the gaps between the design values and actual measurements of the motor's performance are small. Further, an SMPC with a high electrical resistance bears excellent high frequency properties. Such SMPCs have been increasingly used in mass-produced high frequency products, such as fuel injection valves in diesel engines and boost converter reactors for electric vehicles.[3]-[5] In the same way, the SMPC used in a motor can suppress energy loss from the high-frequency noise generated by an inverter.

3. Application to Axial Gap Motors

3-1 Overview of axial gap motor

An AGM is characterized by its thinness and high torque. A structural diagram of an AGM is shown in Fig. 1. In a commonly used RGM, stators and a rotor are positioned cylindrically, while in an AGM disc-shaped stators and rotors are laid out in layers orthogonally around the rotating shaft. In a thin RGM, the facing area between the stators and the rotor is reduced, causing a reduction in torque, whereas an AGM keeps the area unchanged, thereby maintaining a high torque.

The following section explains the soft magnetic core of the motor stator. An RGM magnetic core can easily be produced using magnetic steel sheets as the magnetic paths in the RGM are two dimensional. On the other hand, in the double-stator AGM shown in Fig. 1, three-dimensional magnetic paths need to be created between the rotor and the two stators. It is very difficult to produce the magnetic core for this AGM using magnetic steel sheets as each sheet needs to be cut to a different width and the layering has to be vertical rather than horizontal. Usage of powder offers a highly flexible shaping capability and magnetic isotropy, which in turn delivers high productivity and high performance.

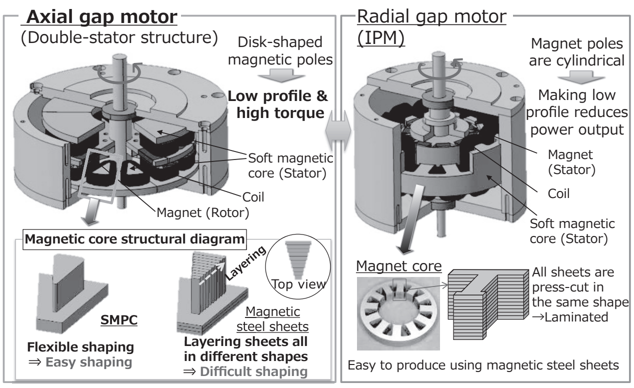


Fig. 1. Motor structures

3-2 Magnetic properties of the soft magnetic powder core for the motor

An SMPC for a motor is required to have high magnetic flux density for an increased torque and low energy loss in the core (core loss) for improved work efficiency. HB2, which is one of Sumitomo Electric's SMPC grades, achieves high magnetic flux density and low core loss as a driving motor. This section describes the magnetic properties of the HB2. Figure 2 shows the DC magnetization curves of the HB2. Compared to the model made of magnetic steel sheets, the HB2 has high magnetic flux density in a high magnetic field, retaining high performance without having magnetic saturation. Next, comparisons of the core loss characteristics of the HB2 and a core made of magnetic steel sheets are shown in Fig. 3. One of

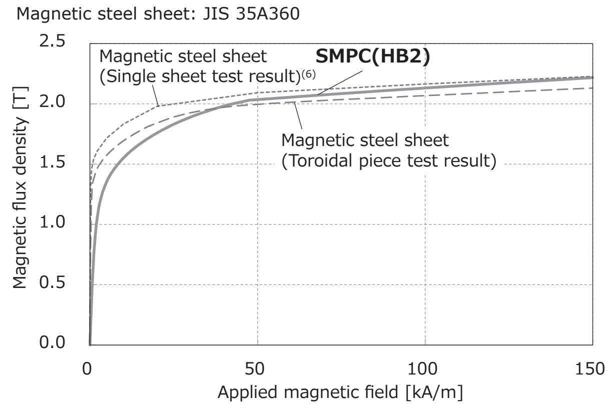


Fig. 2. DC magnetization curve s of soft magnetic powder core for a motor

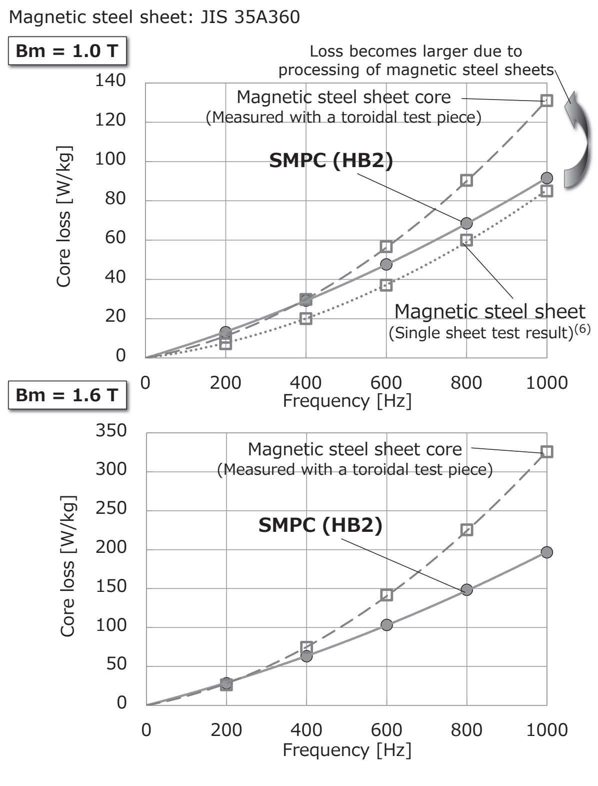


Fig. 3. Core loss characteristics of soft magnetic powder core for a motor

the comparative items for the HB2 was a test piece made of layers of 0.35-mm-thick magnetic steel sheets (JIS 35A360), which are commonly used in motors, in a toroidal form. Compared to this, the HB2 has excellent characteristics in a high frequency condition and a high magnetic flux condition. For example, the HB2 achieves 40% less core loss at Bm = 1.6 T/1kHz compared to the magnetic steel sheet core.

Sumitomo Electric provides the performance data of the HB2 and other SMPC products, including temperature characteristics between –30°C and 150°C, to JMAG-Designer. This data can then be utilized in the design and analysis of motors and electromagnetic components.

3-3 Design and appraisal of axial gap motor

(1) Electromagnetic analysis and design of axial gap motor

As described in the previous section, the HB2 is Sumitomo Electric's low core-loss SMPC for motors. We obtained actual performance data of the HB2 and compared it with that of an RGM, which uses a core made of magnetic steel sheets. Both motors employed a permanent magnet structure. The AGM was equipped with two stators along with a coreless rotor in which magnets were fixed on a non-magnetic support disc. The RGM was an inner-rotor IPM motor. The motor design specifications in this comparison were as follows:

1) Volume occupied by motor: 0.392 L
2) Magnet weight: 89.2 g
3) Coil space factor: 40%
4) Number of poles: 10; Number of slots: 12

The above volume occupied by the motor is obtained by multiplying the external diameter by the height of the motor. The height of the RGM is the distance between the top and bottom ends of the coil. Materials for the components (other than the SMPC) were as follows: Magnetic steel sheets: JIS 35A360; Neodymium (Nd) sintered magnet:*[4] NMX-37SH produced by Hitachi Metals, Ltd. (Data taken at Br = 1.14 T and 80°C); Nd bonded magnet:*[5] S5B-17ME produced by Aichi Steel Corporation (Data taken at Br = 0.81 T and 80°C).

Two types of AGMs and an RGM were used for the comparison. One AGM was equipped with an SMPC and Nd sintered magnets for the rotor. The other AGM was equipped with an SMPC and Nd-bonded magnets for the rotor. The RGM was made of magnetic steel sheets and Nd-sintered magnets. Each motor was designed to be a thin at an aspect ratio of 0.376 (outer diameter of 110 mm and height of 41.3 mm). We first analyzed the electromagnetic fields of the AGMs and the RGM. The analysis conditions were as follows: operating temperature 80°C; rotation 6,000 rpm; and current density 4 $Arms/mm^2$. Figure 4 shows the analysis results of instantaneous torque waves. The AGM that employed an SMPC and Nd-sintered magnets showed nearly twice the torque of the RGM. The AGM that employed Nd-bonded magnets, which have weaker magnetic power, still showed 1.5 times more torque than the RGM. These results demonstrate that this axial structure offers significantly improved torque even in a thin design. Figure 5 summarizes the analysis results for both the loss and efficiency of each motor. The AGM with Nd-sintered magnets showed a very large rotor loss. This was due to the coreless rotor in the AGM, which allows the magnetic flux of the stators to pass through the magnets, causing eddy currents by the electromagnetic induction inside the Nd-sintered magnets of a low electrical resistance. On the other hand, the AGM with Nd-bonded magnets showed better overall efficiency with higher output (torque) despite a larger loss than that of the RGM. This is because the high electrical resistance of the Nd-bonded magnets suppresses the generated eddy currents.

The above results suggest that the AGM with the SMPC and Nd-bonded magnets is the best candidate to achieve high torque and high efficiency as a thin motor. Figure 6 shows the relationship between the aspect ratio and torque of the AGM with the SMPC and Nd-bonded magnets and the RGM. In our analysis, we set the motor

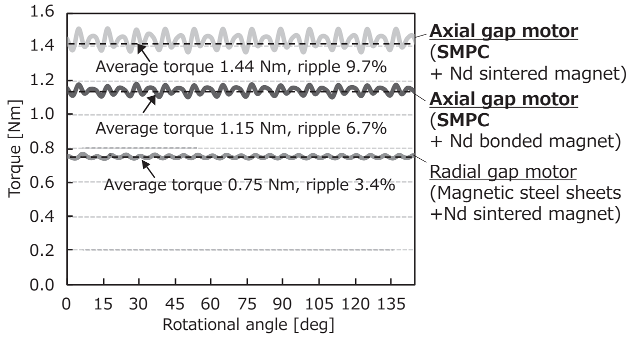


Fig.4. Analysis results of instantaneous torque waves

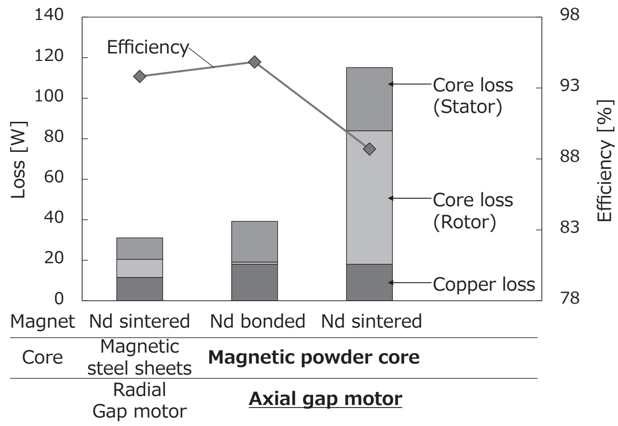


Fig. 5. Loss and efficiency analysis results for each motor

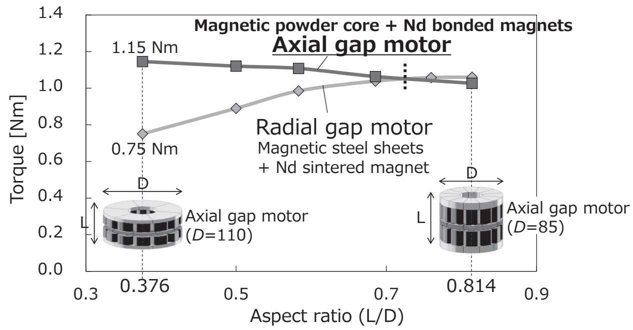


Fig. 6. Torque and aspect ratio of each motor

volume to be constant and varied the aspect ratio. In the RGM, the torque is reduced by about 30% as the shape becomes thinner. The AGM, however, retained high torque even with a low aspect ratio. The torque of the AGM surpasses that of the RGM at an aspect ratio of 0.75. This result suggests that the thinner the shape, the higher the torque efficiency in the AGM.

(2) Performance data of actual axial gap motor

We then built the actual motors and examined their performance. Figure 7 lists all the production motors. The motor was made to be thin at the same aspect ratio as the analysis model: 0.376 (outer diameter of 110 mm and height of 41.3 mm). The AGM employed Sumitomo Electric's HB2 SMPC and Nd-bonded magnets, and the RGM employed JIS 35A360 magnetic steel sheets and Nd-sintered magnets. Figure 8 shows the SMPC compacted specifically for this motor used in the performance test. The net-shape method simplified the core production despite its complicated form comprising teeth and back yoke. This core was made from six pieces as production motor also served as a trial for segment production, which will be used in the future commercialization of large high-power motors, such as driving motors. Note that it is also possible to create the core as a single piece. Table 2 lists the appraisal results for the actual products. Although the AGM prototype used the Nd-bonded magnets that have weaker magnetic power, still it showed 1.6 times higher torque than that of the RGM. The AGM's efficiency was superior to that of the RGM in all areas of frequency from the high-rotation and high-load area, where benefits from the SMPC are most obvious, to the low-load area. The total maximum efficiency was improved by 1%. The overall performance results of the actual motors confirmed that the thin- AGM with an SMPC achieved high torque and high efficiency, proving its excellent motor performance.

Note that the results described in this section are obtained from the joint research undertaken with Masatsugu Takemoto, Associate Professor, Graduate School of Information Science and Technology, Hokkaido University.

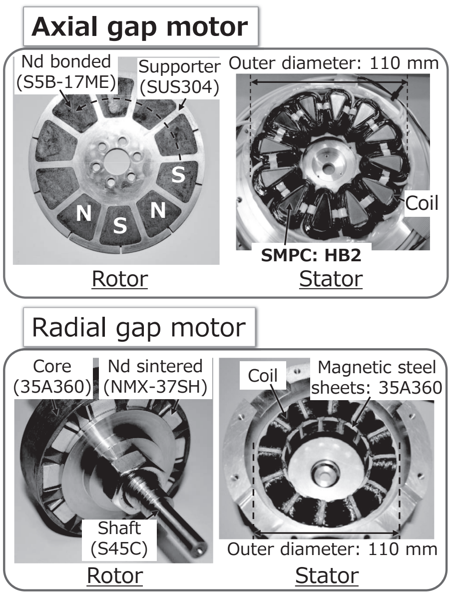


Fig. 7. Production motors

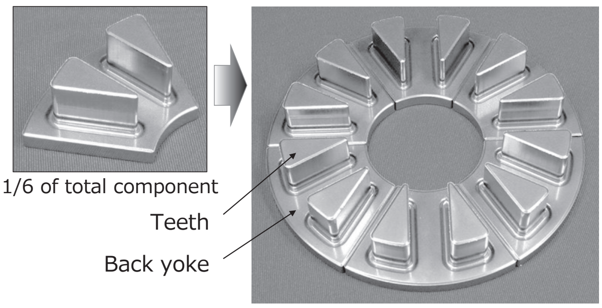


Fig. 8. Soft magnetic powder core for an axial gap

Table 2. Performance results for the production motors

			Axial gap motor	Radial gap motor
Motor dimensions			Φ110×41.3 (Aspect ratio 0.376, **thin shape**)	←(Same aspect ratio)
Core			**SMPC** (HB2)	Magnetic steel sheets (35A360)
Magnet			Nd bonded (S5B-17ME)	Nd sintered (NMX-37SH)
Torque*1		Analysis	1.23 (Nm)	0.81 (Nm)
		Measurement	**1.18 (Nm)**	0.74 (Nm)
Efficiency	Max. value	Analysis	**94.8%**	93.8%
		Measurement*2	94.1%	93.1%
	Low Load*3	Analysis	**88.0%**	87.3%
		Measurement*2	87.5%	87.3%

*1 Measurement condition: 1000 rpm, 4 Arms/mm^2,
*2 Mechanical loss was deducted by using a dummy rotor,
*3 Measurement condition: 1000 rpm, 0.3 Nm

4. Future Prospects for New Materials and Technology

4-1 Reduction of core loss and strengthening of soft magnetic powder core

Improvement in the material properties of the SMPC is essential to achieve even better AGM performance. One such material improvement is core loss reduction. The core loss performance of Sumitomo Electric's new HX3 core is shown in Fig. 9. The HX3 realized lower core loss than the HB2 by controlling the composition of the metal powder and creating a super-thin insulation coating using the company's exclusive technology. The performance results of the HX3 compare well with not only the actual measurement figures of the popular 0.35 mm-thick magnetic steel sheets, but also with those made of 0.3 mm- or 0.2 mm-thin sheets. Therefore, the HX3 core will surely contribute to improved motor efficiency.

Another motor performance improvement factor is the strengthening of the core. Figure 10 shows the strength comparison between the improved core and Sumitomo Electric's HB1. We improved the strength of the core by reducing the breaking points on the core surface through smoothing treatment and by suppressing crack formation through internal hole structure control. The following three-point flexural test revealed that the core elasticity had been improved 1.6 times over the HB1 and with three times better tensile strength. The strength improvement enhances core shaping flexibility. For example, it is extremely difficult to produce is a 0.8 mm-thin core using magnetic steel sheets, however, it can easily be produced with magnetic powder as shown in Fig. 11.

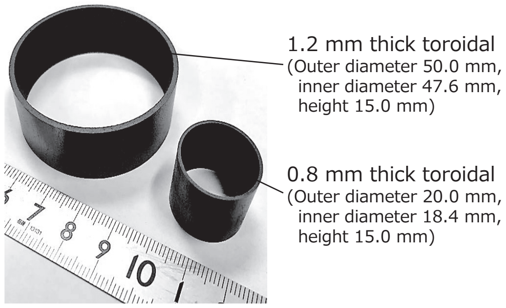


Fig. 11. Thin wall soft magnetic powder core

0.35 mm magnetic steel sheet: JIS 35A360
0.30 mm and 0.20 mm magnetic steel sheet:
30HX1600 and 20HTH1200 produced by Nippon Steel & Sumitomo Metal Corporation

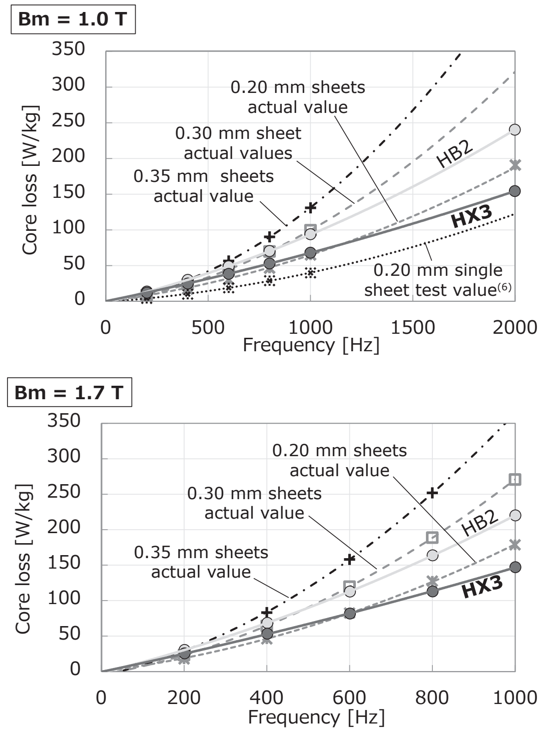


Fig. 9. Core loss reduction in soft magnetic powder core for a motor*6

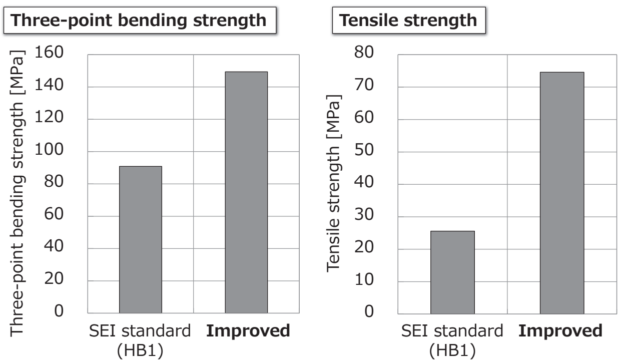


Fig. 10. Improvement of soft magnetic powder core's strength for a motor

4-2 Insulation coating technology

To install coils around the soft magnetic core for a motor, the dielectric strength between the core and coil needs to be maintained using insulation paper or resin. However, such insulation is usually several hundred μm thick, which reduces the coil space factor and keeps the coil and core distance rather large, thereby reducing the motor power. Also, the said distance hinders thermal dissipation from the coil to the core, limiting the maximum current, and this becomes a bottleneck to motor power improvement. The effective solution to this problem is insulation coating over the magnet core surface. Figure 12 shows an appearance view of the insulation-coated motor magnet core and a section view of the edge between the core and the coat. The coat thickness is approximately 50 μm and the dielectric strength is 2,500 V at maximum. Thus, this thin coating technology with high dielectric strength further improves motor power by eliminating the insulation components and increasing the coil space factor.

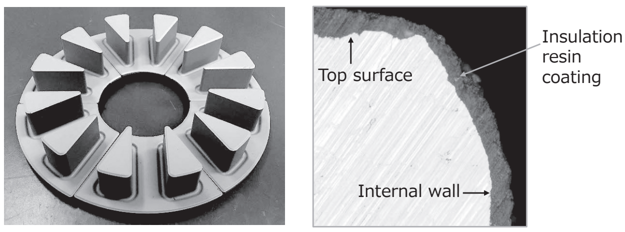


Fig. 12. Insulation coating appearance and section view

4-3 Electromagnetic analysis and design of the motor

This section explains the purpose for Sumitomo Electric, a manufacturer and seller of SMPCs, to conduct electromagnetic analysis and design of an AGM. The shape of an axial core is usually determined based on the optimum electromagnetic design and does not take account of the actual production process due to the complexity of three-dimensional magnetic paths, which tends to cause problems in commercialization. It is, therefore, necessary to establish a design method to attain high motor performance in an easily producible form. When consideration to producibility and impact assessment (electromagnetic analysis) of the actual motor performance are handled by different organizations or companies, it can take an extended period of time to reach the optimum design as the two organizations may require a number of discussions and subsequent adjustments. Sumitomo Electric has built its own electromagnetic analysis technology in order to design the optimum shape of axial magnet cores with a minimum time span. The company also offers a service to produce a motor based on given specifications (e.g. required torque, number of rotations, and size) through our exclusive electromagnetic analysis and design. Figure 13 presents sample performance data of an actual motor produced based on our analysis and design. With the above service, we can quickly offer the benefits of an AGM with an SMPC, such as profile reduction and torque improvement, to a wide market.

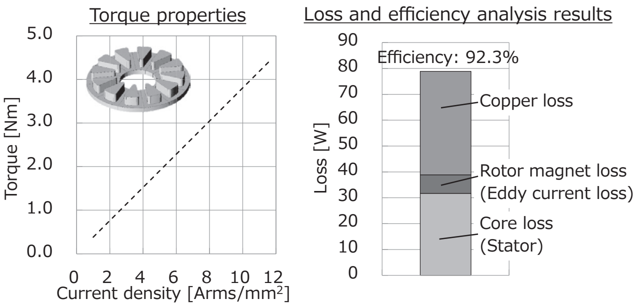


Fig. 13. Performance analysis results of AGM designed by Sumitomo Electric

5. Conclusion

This paper described performance analysis of an AGM using a SMPC and a performance appraisal using an actual AGM produced based on the analysis.

A summary of the said performance analysis and appraisal results is as follows:

1. The SMPC has excellent features in (1) magnetic isotropy, (2) shaping flexibility, (3) performance of the production model, and (4) high frequency properties.
2. As a result of electromagnetic analysis, the AGM with the SMPC and Nd-bonded magnets delivered high torque and high efficiency at the same time.
3. The lower the aspect ratio (i.e. the thinner the shape), the higher torque efficiency deriving from the axial structure.
4. As a result of the actual motor performance appraisal, the AGM achieved 1.6 times higher torque than the RGM made of magnetic steel sheets and Nd-sintered magnets. The AGM also showed better efficiency in all frequency zones.
5. Sumitomo Electric has built a motor analysis and design method alongside the development of materials with better performance and better added value. This will contribute to the performance improvement of motors with SMPCs.

6. Acknowledgements

We would like to express our appreciation to Associate Professor Takemoto, Graduate School of Information Science and Technology, Hokkaido University, for his guidance and cooperation concerning the electromagnetic analysis and performance appraisal of the motors.

Technical Terms

*1 Magnetic steel sheet core: A soft magnetic core made of layers of thin iron-silicon alloy sheets. The thinner the sheet thickness, the lower the core loss; however, producibility is also lowered, making production more expensive.

*2 Saturation flux density: The maximum magnetic flux density that can be generated in a magnetic material (the amount of magnetic flux per unit area). As the saturation flux density becomes higher, the smaller the core size that can be produced.

*3 Net-shape production: Powder metallurgy (metal-forming technology) that produces a complicated form of a complete work without mechanical or other post formation processing.

*4 Nd-sintered magnet: A magnet made of Nd magnetic powder with its density increased to almost 100% (true density) through high heat treatment. The magnetism is very high but the producible shapes are limited and post-processing is indispensable, therefore, production becomes expensive. The electrical resistance is low as it is bulk metal.

*5 Nd-bonded magnet: An injection-molded or pressure-formed magnet made from kneaded Nd-magnetic powder and resin. Its magnetism is less than that of a sintered magnet, as the density of the bonded magnet is lower. However, it has more flexibility in shaping, and insulation from the resin provides high electrical resistance.

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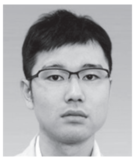

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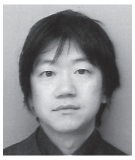

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