Enhanced Functionality of Soft Magnetic Composites for High-Performance Axial Gap Motors

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The advancement of electric mobility as well as improvement in the efficiency of home appliance and industrial equipment have led to a need for higher performance motors. Axial gap motors (AGMs) are attracting attention as a motor that meets the need because of their low profile and high torque compared to radial gap motors. We have demonstrated the high torque and high efficiency of AGMs with soft magnetic powder composites (SMPCs) and started mass production of SMPCs for AGMs. In order to contribute to the further adoption of AGMs, we have developed a low-loss SMPC, pole-shoe teeth core, and thin-insulation-coated SMPC.

Keywords: soft magnetic powder composite, electric motor, axial gap, low profile, high torque

1. Introduction

Against the backdrop of growing calls for environmental friendliness, extensive efforts are being directed at promoting electric mobility and improving the efficiency of home appliances and industrial equipment. Electric motors are key devices critically affecting the performance of these applications. As demand for them has grown, the importance of making them small, light, and efficient has become ever more apparent. Radial gap motors (RGMs) are a type of motor in common use today. Their performance has improved through control method developments and the improved performance of motor components including cores, copper windings, and magnets. Meanwhile, RGMs have their drawbacks including that the torque decreases with thin shape, which is attributed to their motor structure. Consequently, axial gap motors (AGMs) have come into focus. Compared with RGMs, AGMs develop high torque with a thin-shape design. However, unlike RGMs, AGMs require a three-dimensionally shaped core, which is difficult to manufacture using the magnetic steel sheets*[1] conventionally used in electric motors. Therefore, AGMs have been in use only to a limited extent.

We developed soft magnetic powder composites (SMPCs) with superior magnetic isotropy and a high degree of geometric freedom. We have been mass-producing them for diesel engine fuel injection valves, boost converter reactors for hybrid vehicle, and ignition coils.[(1)–(3)] Drawing on years of experience in these technologies, we developed SMPCs for AGMs and demonstrated their superiority for motor performance[(4)] and began mass-producing AGM cores in August 2020 (Photo 1). Their use is expected to expand in the future. For example, AGMs with the industry's highest level of power density per unit weight were recently selected for the mass production of traction motors for use in hybrid electric vehicles[(5)]. Thus, expectations are high for the increasing use of AGMs in the future. This article reports on the features and the latest development status of our SMPCs and the advantages gained from applying them to AGMs.

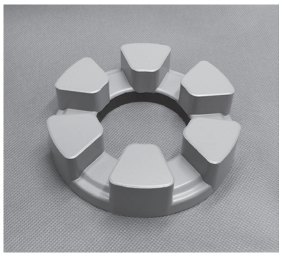


Photo 1. AGM core in the beginning phase of its mass production

2. SMPC: Overview and Features

2-1 Overview of SMPC

SMPCs are compacted using insulation-coated iron powder and are completed through heat treatment, which is intended to remove strain introduced during compaction process. Using pure iron or an iron-based alloy with a high saturation flux density*[2] and superb plastic deformation capacity, our SMPCs ensure a balance between high flux density and excellent AC magnetic properties through high-density compacting without breaking the insulating coating a few tens of nanometers in thickness.

Unlike magnetic steel sheets, SMPCs with a virtually uniform material structure in every aspect are magnetically isotropic. Moreover, SMPCs are highly suitable for cores that require three-dimensional magnetic circuits, such as in AGMs, since they are net-shape-production*[3] by filling a mold with a powder suitably meeting various geometric requirements.

Furthermore, while the measurements obtained from single sheets before lamination are generally listed in catalogs of magnetic steel sheets, their magnetic properties degrade due to stresses and thermal strains resulting from stamping, staking, welding, and other product-shaping processes. This is a cause of the differences between design values and measurements regarding motor performance.[(6),(7)] In contrast, with SMPCs, specimens used to acquire magnetic property data for design purpose are produced through a similar process to shaped products. Consequently, one advantage of SMPCs is small differences between design values and measurements in products.

2-2 SMPC material properties

Motor cores are required to have a high flux density contributing to high torque and a low energy loss in the core contributing to efficiency (hereinafter, "iron loss"). Table 1 presents the DC-BH and iron loss characteristics of our SMPCs and magnetic steel sheets for motors. The SMPC HB2 exhibits a higher flux density in the high magnetic-field region than the magnetic steel sheets do, enabling it to avoid decreases in torque resulting from the magnetic saturation of the core. This comes from the high-density compacting of our SMPCs using an iron powder with a higher saturation flux density than magnetic steel sheets.

Compared with magnetic steel sheets 0.35 mm in thickness used in general electric motors, the HB2 exhibits an advantage in iron loss even in the low-frequency range often used by motors. The advantage increases in higher-flux and higher-frequency ranges. Moreover, the HX3 developed with the aim of making the core further low-loss exhibits properties comparable to those of the low-loss grade magnetic steel sheets 0.20 mm in thickness.

Moreover, because the SMPC is a low-iron-loss material in the high-frequency range, the material is expected to suppress energy losses increasing due to high harmonics generated in an inverter-powered motor. We in practice evaluated the iron-loss characteristics of inverter-powered motors. The SMPC showed diminished high-harmonic components superimposed on its hysteresis loop*4, as shown in Fig. 1. Consequently, while the magnetic steel sheets exhibited 10% or more increases in loss resulting from imposed high harmonics, the SMPC suppressed the increase to approximately 3%.

Table 1. Magnetic properties of SMPCs and magnetic steel sheets(8)

Material		Magnetic Flux density (T)			Iron loss (kW/m³)			
					Bm = 1.0 T		Bm = 1.7 T	
		$B_{2kA/m}$	$B_{20kA/m}$	$B_{50kA/m}$	400 Hz	1 kHz	400 Hz	1 kHz
SMPC	HB2	1.02	1.76	2.04	221	696	513	1640
	HX3	0.66	1.66	1.81	146	413	311	912
Magnetic steel sheet	0.35 mm-thick (JIS 35A360)	1.45 (1.60)	1.90 (1.98)	2.00 (2.09)	227 (153)	1006 (650)	628	2760
	0.30 mm-thick (30HX1600)	-	-	-	178 (109)	734 (433)	474	1996
	0.20 mm-thick (20HX1200)	-	-	-	128 (82)	487 (304)	344	1335

※Measurements of toroidal specimens
※Figures in parentheses: values from single-sheet testing

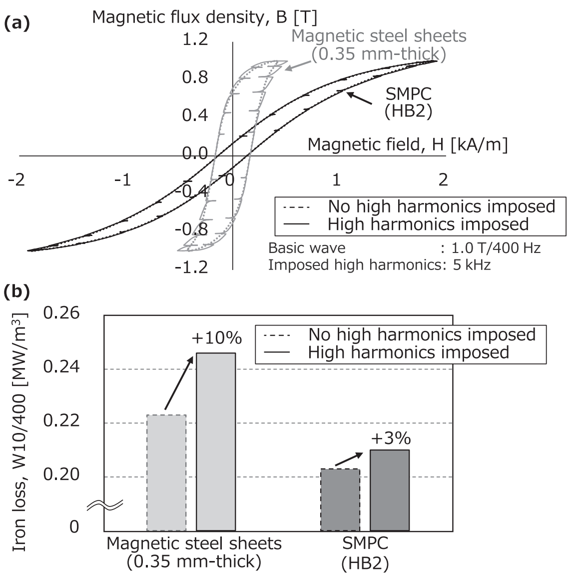


Fig. 1. Differences in hysteresis loop (a) and iron loss (b) with high harmonics imposed and not imposed

3. Application to Axial Gap Motors

3-1 Overview of axial gap motor

SMPCs are superior to magnetic steel sheets in terms of performance, as described above. To be a competitive motor even with costs taken into account, it is preferable to apply an SMPC to a motor, like an AGM, that benefits from the extra degree of geometric freedom of SMPC.

An AGM is a motor that develops high torque from a thin-shape design. It is structured as schematically shown in Fig. 2. While conventionally predominant RGMs have a structure in which the stator and rotor are arranged cylindrically, AGMs are structured so that the stator and rotor are overlaid in the direction of the axis of rotation. In a thin-shape design, RGMs develop reduced torque due to a reduced facing area between the rotor and stator. In contrast, AGMs maintain high torque because the facing area between rotor and stator remains unchanged.

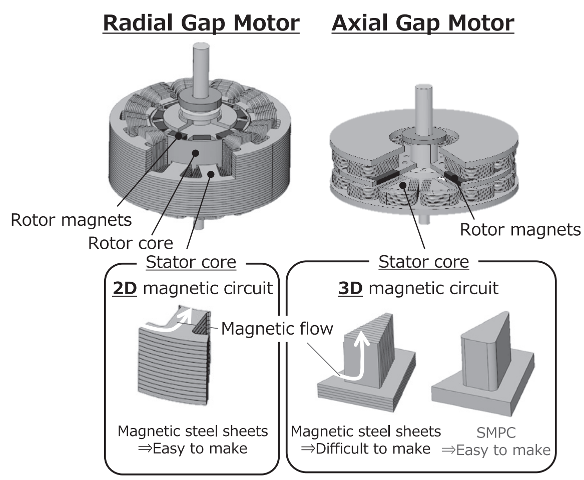


Fig. 2. Different motor structures

For RGMs comprised of two-dimensional magnetic circuits, using magnetic steel sheets, it is easy to construct a core. In contrast, AGMs require three-dimensional magnetic circuits to be formed. To use magnetic steel sheets to construct them, required techniques include lamination of sheets varying in width, joining steel sheets to change the direction of lamination, and wire winding round a wound core. These requirements lead to greater manufacturing difficulty and higher cost. In contrast, using SMPCs with magnetic isotropy and a high degree of geometric freedom, it is easy to construct cores for AGMs. Consequently, on top of the aforementioned performance benefits, SMPCs are expected to facilitate the commercialization of AGMs.

3-2 Properties of SMPCs and motor efficiency improvement

Using the parts and configurations illustrated in Fig. 2, we have compared and evaluated motor performance under the preconditions of identically sized and flat-shaped RGMs and AGMs. We have proved, through analysis and use of actual motors, that AGMs develop about 1.6 times the torque of RGMs with a 1% higher maximum efficiency.(4) In this verification, the SMPC used in the AGM was the HB2. Additionally, the newly developed material HX3 with further reduced iron loss, as shown in Table 1, was used to evaluate motor performance using it as the stator core in the AGM. The same design specifications, including the geometry of the stator core, as those of the conventional AGM were used (Table 2).

Table 2. Design specifications for the tested motor

Volume of motor		0.392 ℓ (Φ110 × 41.3 t)
Rotor	No. of pole	10
	Magnet weight	89.2 g
	Magnet material	S5B-17ME
Stator	No. of slot	12
	Core materials	SMPC: HB2, HX3
	Space factor of coil	40%
Maximum rotational speed		6000 rpm
Operating temp. (CAE)		80°C

Figure 3 presents efficiency maps for each motor. Using the HX3, the motor efficiency improved by 1% to 2% across almost the entire operating region in comparison with the use of the HB2. Consequently, the HX3 is effective for improving the motor efficiency, as intended. Meanwhile, Fig. 4 plots the torque characteristics of the AGM incorporating the HX3, which were largely similar to those of using the HB2. Comparisons of the DC-BH characteristics of the HB2 and HX3, presented in Table 1, show that the HX3 had lower magnetic permeability*5 than the HB2. Despite this general disadvantage in terms of torque characteristics, the HX3 exhibited a contradictory result.

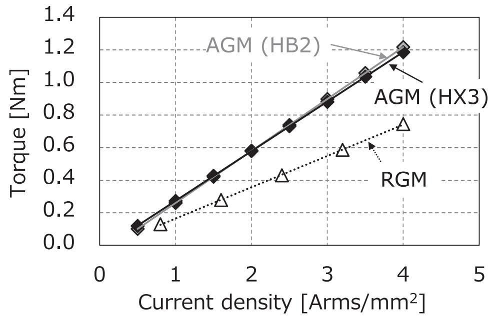


Fig. 4. Torque characteristics of newly developed AGMs

One reason for this result is that, in the structure of the AGM under development by us, the extent of the stator core's influence on the overall magnetic resistance*6 of the motor is not dominant. Our AGM has an air gap of 1.0 mm between the rotor and stator, which is wider than those of general RGMs—including our RGM built for comparison purposes—designed to approximately 0.5 mm. Moreover, in our AGM, the number of air gaps per magnetic circuit is twice greater than those of RGMs. The magnetic resistance of the AGM used for the current verification was calculated (Fig. 5). Even if the magnetic permeability of the stator core decreases to half that of the HB2, the overall magnetic resistance of the motor increases only by 1.9% and the torque decreases by no more than 1.9%. In addition, other analysis results show that, even with a similar iron loss to that of the HB2, magnetic permeability decreasing to one-fifth leads to approximately 1% improvement in motor efficiency in the light load and high rotational speed regions.(8) These findings are contradictory to the conventional requirement that the motor core material should have high magnetic permeability. Yet this result suggests a novel material development option, that is to reduce iron loss even sacrificing magnetic permeability, depending on the motor configuration—not limited to AGMs—and in which operation region to improve motor efficiency. Moreover, in line with these development guidelines, we have developed a material with another 40% iron loss reduction from the

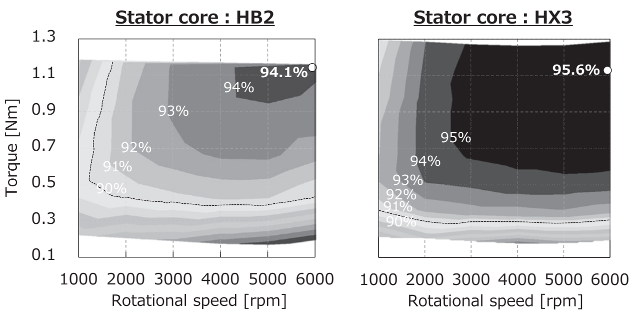


Fig. 3. Efficiency maps of newly developed AGMs

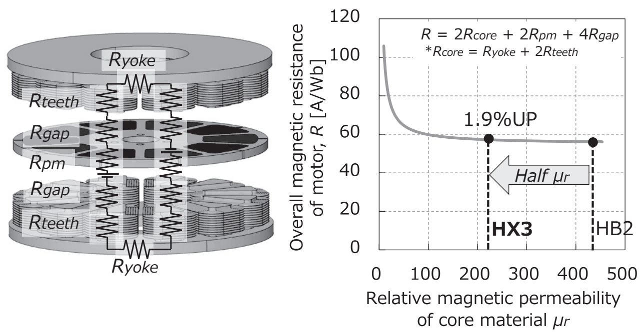


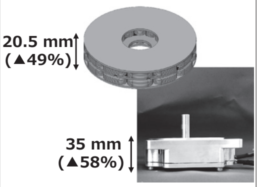
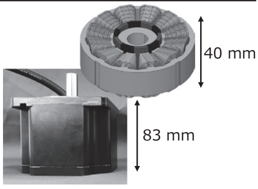
Fig. 5. Magnetic resistance of AGM vs. magnetic permeability of core

HX3 and are evaluating it on actual motors. While it is not easy to alter the magnetic permeability of magnetic steel sheets, SMPCs enable magnetic permeability to vary through changes to the thickness of the coating, iron powder particle size, and compacting density. Consequently, a feature of SMPCs is that the material gives another degree of freedom in motor design.

3-3 Motor downsizing by AGM design

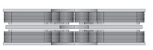
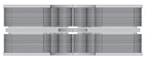
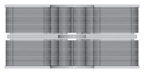
While the foregoing discussion described that, given identical size, AGMs develop higher torque than RGMs, practical applications require downsized motors without compromising performance. To meet this challenge, we studied how much commercially available RGMs can be downsized by turning them into AGMs. Table 3 provides an example comparison. We designed an AGM using the same radial dimensions and magnet material as a commercially available RGM to develop comparable torque and efficiency. The AGM demonstrated a 58% motor height reduction and a 50% motor weight reduction. Furthermore, the cost of this motor was calculated based on the price per unit weight of the key components, that is, magnet, coil, and core. It was found that the cost could be cut by approximately 15% at the maximum, partly owing to reduced usage of parts made possible by downsizing.

Table 3. Example of motor downsizing by AGM design

	AGM	Commercially available RGM
Motor overview *Outer diameter Φ98		
Weight (Core/Coil/Magnet)	**0.95 kg (▲44%)**	1.7 kg
Weight (including casing)	**1.6 kg (▲50%)**	3.2 kg
Material cost (ratio to RGM)	85～96%	100%
Torque	0.65 Nm	←
Efficiency	90.6%	90.9%

Meanwhile, a lineup of RGMs differing in performance may be offered, using the same stamping dies, yet changing the number of laminated sheets. With AGMs incorporating SMPCs, it is also possible to vary the core height using the same mold. Consequently, as with RGMs, an expanded lineup of AGMs varying in performance can be offered while reducing the mold cost (Table 4).

Table 4. Example of motor performance variation enabled by varying

Motor height	 24.5 mm (Core: 10.1 mm×2)	 35.6 mm (Core: 15.6 mm×2)	 46.7 mm (Core: 21.1 mm×2)
Torque constant Nm/(Arms/mm²)	0.062	0.114	0.178
Max. efficiency	90.4%	92.6%	94.5%

4. Enhanced Functionality of SMPCs

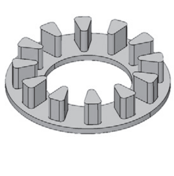
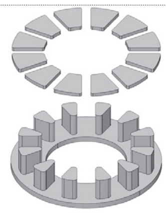
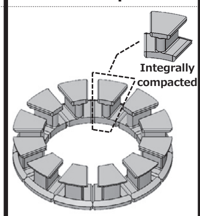
The foregoing discussion described that an AGM design incorporating SMPCs can make motors smaller and improve their efficiency. To augment this advantage further, we are exploring core modeling and working on the development of peripheral technologies, in addition to improving the material characteristics, as described below.

4-1 Molding technology for pole-shoe teeth cores

In general, RGMs have a stator core provided with pole shoes at the teeth ends for improved motor torque and efficiency, reduced motor-originated noise and vibration, and enhanced reliability. Providing pole shoes is also often considered for AGMs because similar effects are observed. To build such a core from an SMPC, it was conventionally impossible to fabricate an integral part consisting of pole shoes, teeth, and a yoke because, after compression molding, the molded part could not be released from the mold. Consequently, pole shoes or a yoke were separately constructed and they were subsequently joined to build a core with pole shoes. This construction method, however, has a few drawbacks: that the need for more than one type of mold is disadvantageous in terms of cost; that clearances at joints reduce torque and efficiency; and that assembled cores show poor accuracy in height, although this accuracy is critical for determining the size of the air gap, which affects motor performance.

We explored technical solutions for these drawbacks, apart from the conventional compacting method, and developed a technique of forming an integral part consisting of pole shoes, teeth, and a yoke, as illustrated in Table 5. This technique requires only one type of mold. Moreover, it has proved itself to enable the compacting accuracy in the direction of core height to improve 10 times or more as compared with the conventional method. Thus, it is likely to lead to improved accuracy in the size of the air gap. Although yoke pieces are joined to each other, AGMs described in Chapter 3 involve similar divisions, and it has been demonstrated through analysis and on an actual machine that this way of division does not affect motor performance. This technology is thought to improve the degree of freedom of AGM design, thereby helping achieve additional performance improvements.

Table 5. Features of the newly developed axial core with pole shoes

	Without pole shoes	With pole shoes	
Torque	1.39 Nm	1.64 Nm (△18%)	
Efficiency	88.9%	91.5% (△1.6%)	
	Conventional	Conventional	**Developed**
Core shape			
No. of core types	1	2	1
Core height accuracy	Good (Similar to common sintered parts)	No good (Large assembly errors)	Very good (High-precision molding achievable)

4-2 Improved insulating coating technology

In the core winding process, insulating paper or a resin bobbin provides insulation between the core and coil. The conventional insulating paper and resin bobbin are 500 µm or more in thickness and take up some space, necessitating a reduced number of turns of the coil for this space. Meanwhile, the coil is one of the parts that become hottest in the motor. By providing the above-mentioned part, a large thermal resistance is produced between the coil and core, degrading the coil's heat dissipation capacity and imposing design restrictions on the motor due to temperature rise. As a solution to this challenge, we have worked on the development of a technology of providing the surfaces of the core with a resin coating a few tens of micrometers in thickness that offers high dielectric strength.[4] Through coating thickness reduction and productivity improvement efforts, a thin and high-insulating coating (0.1 kV/µm or more) has been developed, as shown in Fig. 6. Table 6 presents the verification results for the heat-dissipation merits made possible by this technology. One sample core had windings with insulating paper between the core and the windings. The other sample core was provided with windings and the newly developed coating. These samples were compared with respect to the maximum temperature reached during electric current application. The use of the newly developed coating contributed to the maximum reachable temperature being 44°C lower than that observed with the use of insulating paper. Thus it becomes possible to apply a higher electric current commensurate with this temperature difference, enabling the motor to be further reduced in size. Furthermore, the reduced number of parts is expected to make motor assembly simpler.

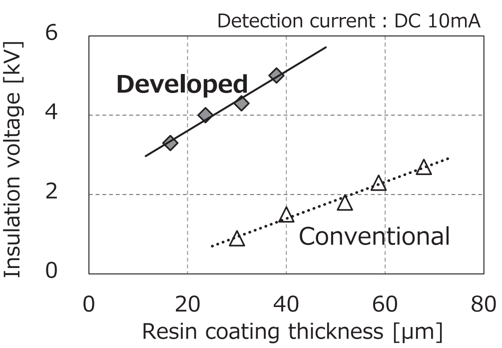


Fig. 6. Insulation voltage of the newly developed coating

Table 6. Heat dissipation comparison of coated core and paper-insulated core

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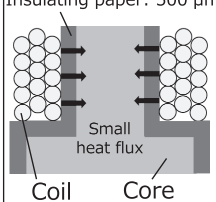
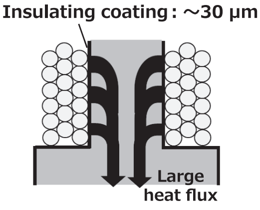
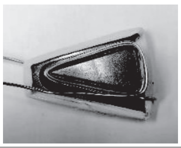
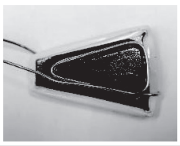
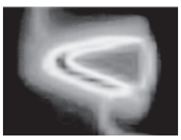
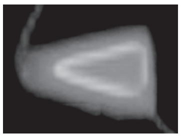
<tr><td>Schematic illustration of sectional view of core</td><td></td><td></td></tr>
<tr><td>Sample</td><td></td><td></td></tr>
<tr><td>Heating state</td><td></td><td></td></tr>
<tr><td></td><td>24°C</td><td>200°C</td></tr>
<tr><td>Max. temp.</td><td>163℃</td><td>119℃</td></tr>
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5. Conclusion

We improved the performance of SMPCs, demonstrated the material's use in axial gap motor (AGM) design for motor downsizing and efficiency improvements, and established novel development guidelines for motor cores toward a low-carbon society. We also demonstrated an AGM that halves both volume and weight with the same performance for commercially available radial gap motor, and showed that it can contribute to cost reduction. Furthermore, it developed a pole-shoe teeth core with superb productivity and an insulation coating technology for thin and high-insulating coatings to enhance the advantages of AGMs. In addition to these, we are working on the development of peripheral technologies such as for fixing SMPCs[10] and an innovatively structured AGM[11] to help AGMs come into wider use.

6. Acknowledgements

We are deeply grateful to Professor Takemoto and Dr. Tsunata at the Graduate School of Natural Science and Technology, Okayama University for their invaluable guidance and support for our electromagnetic analysis of motors and evaluation of actual motors.

Technical Terms

*1 Magnetic steel sheet core: Thin sheets of iron-silicon alloy, laminated to form soft magnetic cores. Generally, their iron loss characteristics improve with decreasing sheet thickness; however, this is costly due to declining productivity.

*2 Saturation flux density: The maximum flux density (the amount of magnetic flux per unit area) reachable by a magnetic material. Higher saturation flux density enables making cores smaller.

*3 Net-shape production: A powder molding process used to obtain a final product shape simply through pressure molding using a mold without the need for a post-process such as machining.

*4 Hysteresis loop: The flux density of a magnetic material changes differently in response to an increase or decrease in the field strength, forming a curve known as a hysteresis loop.

*5 Magnetic permeability: The factor of proportionality determined when expressing the relationship between the field strength H and the flux density B by: $B = \mu H$. Higher flux density can be achieved from higher magnetic permeability at a lower coil current.

*6 Magnetic resistance: A measure of how strong opposition the magnetic flux encounters in a magnetic circuit.

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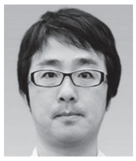

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