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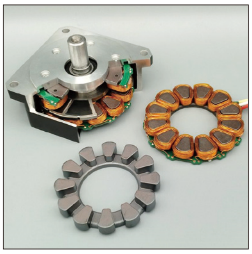

Contributing to a Sustainable Society with Axial Flux Machines and Soft Magnetic Composites

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We have developed soft magnetic composites (SMCs) and an axial flux machine (AFM) utilizing SMCs to contribute to the advancement of a sustainable society. The estimated CO_2 emissions from SMC manufacturing are approximately one-quarter of those produced during magnetic steel sheet manufacturing. Additionally, we have developed a recycling technology that allows for the reuse of powdered motor stator as raw material for SMCs while demonstrating consistent magnetic properties before and after recycling. Furthermore, our innovative design of a 75 kW-class AFM with a power density of 12.6 kW/kg illustrates the effectiveness of SMCs and AFM in reducing material usage. Finally, we have confirmed that our 20 kW-class AFM, which incorporates low CO_2 emission ferrite magnets, matches the size, power, and efficiency of a radial flux machine utilizing Nd sintering magnets.

Keywords: axial, soft magnetic composite, thin and high torque, sustainable, recycle

1. Introduction

Motors can efficiently convert electrical energy into driving power, and their demand has been growing continuously. Today, various types of motors account for more than half of total electricity consumption.[1] Since the application of motors is expanding, research and development are being conducted actively to improve their efficiency and reduce their size/weight. In addition, in recent years, materials and components must be selected with a focus on the reduction of environmental impact and resource procurement not only at the time of their use but also during their production process. In the case of motors, increasing demand for them is raising an issue related to the supply of magnets, copper wires, and iron core materials (magnetic steel sheets; MSSs), and there is a growing need to recycle each material and component in order to achieve sustainable use of materials in consideration of environmental impact.

At Sumitomo Electric Industries, Ltd., we have developed high-performance soft magnetic composites (SMCs) as motor core materials (hereinafter referred to as “motor core”), as well as their molding technology and peripheral technologies, and have demonstrated the high performance of flat motors by effectively applying the features of these composites to axial flux machines (hereinafter referred to as “AFMs”).[2],[3] After establishing the technology for SMCs with double pole shoes, which is effective for increasing the torque of the motor, we began mass production and delivery of motor cores for air purifiers in June 2023.[4)-(7] Furthermore, in July 2024, we began mass production and delivery of SMCs with a thin and high withstand voltage coating (Fig. 1).[8] The new composites improve the coil space factor and coil heat dissipation of the motors, and they also increase their torque remarkably. In addition, in order to contribute to the progress of a sustainable society through the use of AFMs that take advantage of the SMCs, we are expanding their lineup while promoting the evaluation of their environmental impact and recyclability.

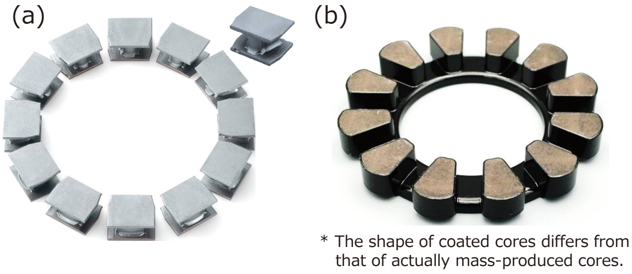


Fig. 1. AFM cores for which mass-production was started
(a) SMC with double pole shoes, (b)Thin insulation-coated core

Furthermore, we took advantage of our unique development technologies to create traction motors having the same size and high efficiency as those of commercial motors by using materials and components with lower environmental impact, higher availability, and lower resource risk. We have also prepared a lineup of trial motors to help various industries easily try out these motors. In this paper, we report our recent activities for expanding the use of the SMCs and AFMs made from these composites.

2. Latest Development of SMCs

2-1 Expansion of material lineup

A concept image of the material lineup is shown in Fig. 2. Since high magnetic flux density and low iron loss cores are usually required to improve the performance of motors, we promoted the development of a material with better magnetic properties than before. On the other hand, our knowledge obtained from motor design to date shows that there are cases where the impact of the magnetic permeability of motor core on the torque characteristics of AFM is little.[9] When motors are designed using conventional SMCs in such cases, the characteristics of the SMCs are excessive. Since motors are industrial products, it is important to achieve cost effectiveness that matches the needs. To make it possible for us to propose materials suitable for various required specifications, we also advanced the development of a material having a better balance of performance and cost than before and a lower-cost material. Table 1 shows the characteristics of the material grades currently in our lineup. Since 2016, material data for the analysis have been registered in the electromagnetic analysis software JMAG, and the data on the newly developed materials have been included in the January 2025 update version of this software.

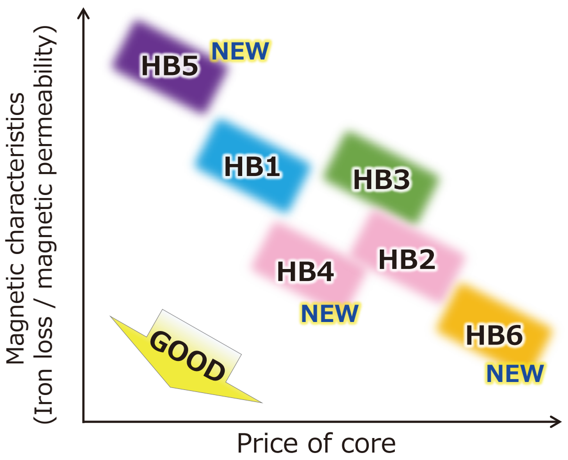


Fig. 2. Schematic illustration of the expansion of SMC lineup

Table 1. Magnetic characteristics of our SMCs

Grade	Coercivity (A/m)	Magnetic flux density (T)			Iron loss (W/kg)			
					Bm = 1.0 T		Bm = 1.5 T	
		$B_{2kA/m}$	$B_{4kA/m}$	$B_{20kA/m}$	400 Hz	1 kHz	400 Hz	1 kHz
HB1 Standard	227	1.07	1.33	1.8	43.9	125.7	85.3	247
HB2 Low loss	107	1.02	1.28	1.76	29.7	93.5	59.7	190.5
HB3 High μ	227	1.15	1.37	1.8	44.6	128.3	89	259.5
HB4 Low loss	139	0.88	1.27	1.84	31.7	93.2	63.7	190.2
HB5 Cost performance	270	0.6	0.95	1.67	53.3	140	98.5	258.4
HB6 Lower loss	123	1.1	1.34	1.79	25.9	72.9	53.2	149.5
Laminated MSS (35A360) measured value	50	1.45	1.57	1.9	30	132.9	66.1	288.5

2-2 Contribution of SMCs to LCA

To contribute to the advancement of a sustainable society, it is important to reduce power consumption of motors, to reduce the CO_2 emissions when motors are produced, and to make motors recyclable after the end of life (Fig. 3). At first, we evaluated the CO_2 emissions during the SMC production process. The target processes for CO_2 emissions calculation included the production process of insulation coating iron powder, which is a raw material, its compaction molding, heat treatment and post-processing of moldings, and their shipping. The amount of CO_2 emitted until the raw material was finished as SMCs was 0.92 to 0.95 kgCO_2/kg,[10] most of which was emitted from the raw material production process, as shown in Fig. 4. On the other hand, it has been reported that the CO_2 emissions during the production of MSSs that are widely used as motor cores today are 1.8 to 3.7 kgCO_2/kg.[11] To compare this value to our calculation value, it is necessary to take into account the amount of CO_2 emissions during the subsequent punching, stacking, and heat treatment processes. While MSSs are usually made from iron ore in a blast furnace, most of the raw iron powder for SMCs is made from scrap iron in an electric furnace. Therefore, the CO_2 emissions during the latter process is less than that during the former process.

Next, we discuss the development of technology that makes SMCs recyclable. The recycling process we propose is shown in Fig. 5. Stators containing SMCs were fed into a crusher, and the crushed materials were sorted according to each component using a screen to extract the crushed SMCs (hereinafter referred to as "recycled powder"). After the recycled powder was mixed with a small amount of lubricant, the powder was subjected to compaction molding and heat treatment in the same way as the usual SMC

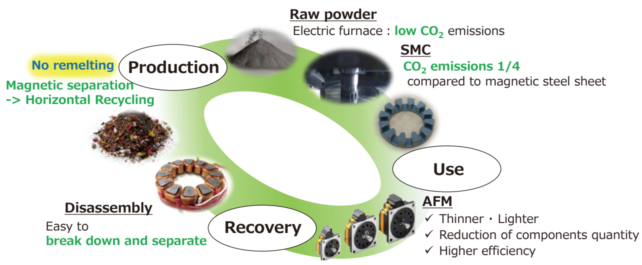


Fig. 3. Schematic illustration of contribution of SMC to the progress of sustainable society

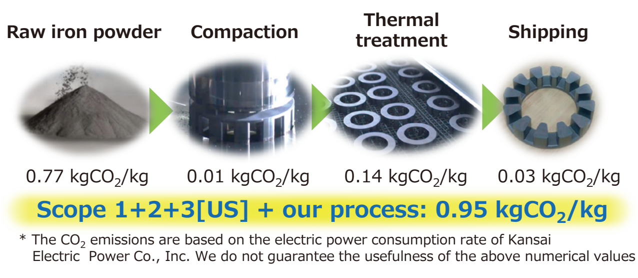


Fig. 4. CO_2 emissions during SMC production process[10]

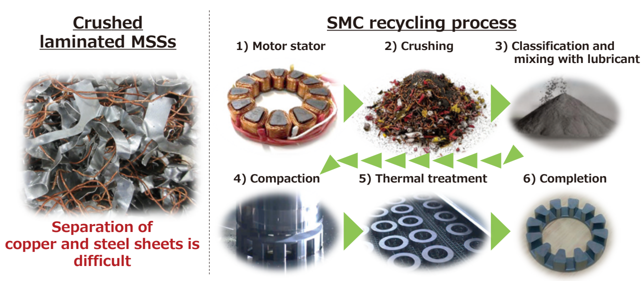


Fig. 5. Targeted SMC recycling process

production process. The particle size of the crushed powder was nearly equal to that of virgin powder, and even when stators containing coils and mold resin were crushed, it was basically possible to separate iron powder from the coils and resin by sieving only. In addition, since stator components other than the core are non-magnetic, iron powder can be sorted out with higher accuracy using a magnetic separator. Figure 6 shows the magnetic characteristics of SMCs made from recycled powder. Damage to the insulation coating in the recycling process was reduced, and an increase in iron loss before and after recycling was significantly suppressed by devising an appropriate process for producing SMCs before recycling and selecting proper particle size distribution/insulation coating of the virgin powder. It was also confirmed that an increase in iron loss between before and after recycling can be suppressed not only in the case of test pieces (ring-shaped) but also in the case of product-shaped cores (Fig. 7). The above results

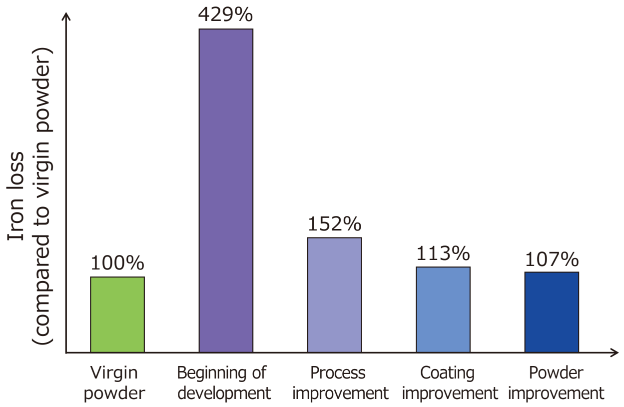


Fig. 6. Characteristics of SMCs made from developed material and process for recycling

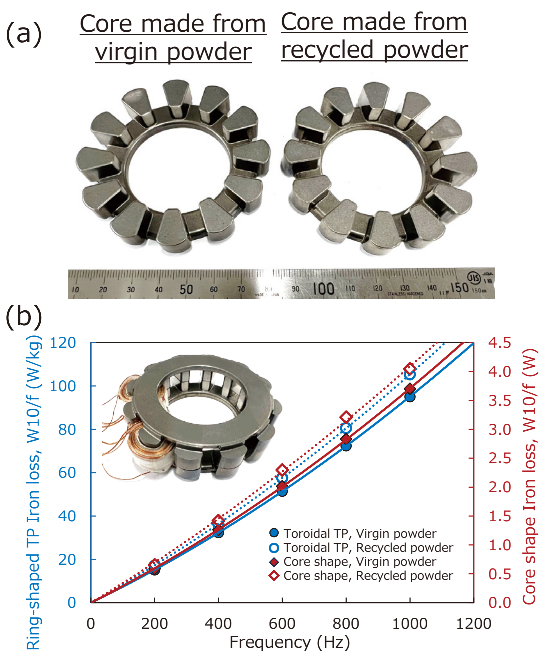


Fig. 7. Characteristics comparison between the shapes of cores made from virgin and recycled powders

were obtained from SMCs made from recycled powder only. However, since the characteristics difference between virgin SMCs and those made from the mixture of virgin and recycled powders decreases, the social implementation of AFMs containing recycled SMCs is expected to expand steadily.

As a comparative example, Fig. 5 shows the results obtained when stators made from laminated MSSs are crushed. Coils and MSSs were intricately twined together and were extremely difficult to separate. Copper is a tramp element in iron refining, and once copper is dissolved in iron, it is difficult to economically remove copper.[12] Therefore, when recycling motors made by using MSSs, extremely burdensome material separation work is required. In contrast, for the recyclable SMCs we have developed, it is enough to only pass the stators containing the composites through an ordinary crusher. The process of reinsulating the iron powder obtained after crushing is also unnecessary, resulting in low CO_2 emissions in the recycling process. The CO_2 emissions from SMCs made from recycled powder are extremely low at about 0.18 $kgCO_2$/kg.

This proves that SMCs can greatly contribute to the progress of a sustainable society.

3. AFM for Which SMCs Are Used

This chapter describes an example of motor design and evaluation, and it additionally shows that AFMs made from SMCs enhance the flexibility in the motor design and that the composites can greatly contribute to the progress of a sustainable society.

3-1 High power density motor

One of the reasons that AFMs have been attracting attention in recent years is that they are suitable for increasing the power density of flat motors. Compared to radial flux machines (RFMs), AFMs make it easier to increase the opposing surfaces area between the stator and rotor, which affects motor torque when the motor shape is flat. In particular, double-rotor-type motors, which are mainly produced by YASA Limited,[13] are often used since the cores are simple in shape and easy to make even from laminated MSSs. On the other hand, double-stator-type motors are advantageous mainly in terms of mechanical structure design and heat dissipation. However, there were few comparative studies on which of the two motor structures is more suitable for increasing power density. Therefore, we also conducted an optimum design of two types of motors with the same specifications to evaluate which of the two motor structures is more advantageous in increasing power density.[14]

Table 2 and Fig. 8 show the design specifications and structure of the double-rotor-type and double-stator-type motors. We designed these motors in pursuit of higher power density under the restriction of same size and power and compared them in terms of power density. As a prerequisite, the magnet weights of both motors, which greatly affect their torque, were equalized. The weight of each designed motor is shown in Fig. 9. Since the double-stator-type motor was 17% lighter than the double-rotor-type motor, the power density of the electromagnetic components of the former motor was very high at 12.6 kW/kg, whereas that of the latter motor was only 10.6 kW/kg. The results of efficiency comparison at principal driving points are also shown in Fig. 10. The double-rotor-type motor was superior to the double-stator-type motor in efficiency at the base speeds and light load operation ranges near the normal operation point, while the double-stator-type motor was more efficient at the maximum torque point, maximum speed, and maximum output power point. The following

Table 2. Design specifications of high power density motor

Max. power output	75 kW
Max. torque	143 Nm
Max. speed	10,000 rpm
Base speed	5,000 rpm
Max. DC-bus voltage	550 V
Max. inverter current	153.2 Arms
Outer diameter	224.8 mm
Axial length	46.5 mm

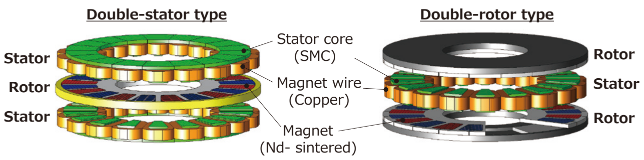


Fig. 8. Structures of high power density motors

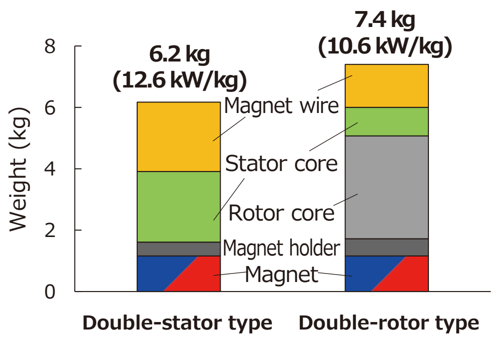


Fig. 9. Weights of designed high power density motors

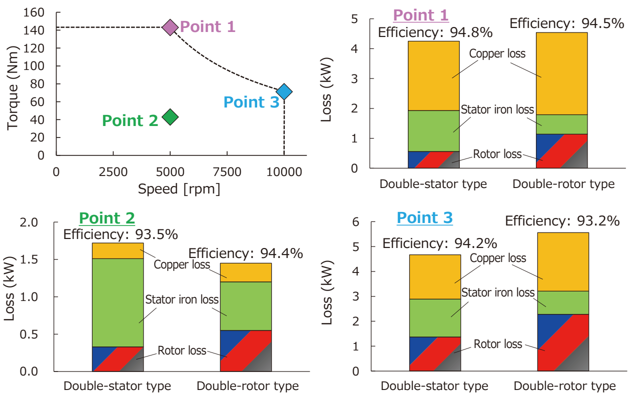


Fig. 10. Loss and efficiency of high power density motors at each operation point

are the reasons that the efficiency of the double-rotor-type motor was higher than that of the double-stator-type motor in the normal operation range. The stator core of the double-rotor-type motor was lighter than that of the double-stator-type motor, and this made it possible to reduce the iron loss in the normal operation range, where the iron loss accounts for a substantial fraction of the total loss.

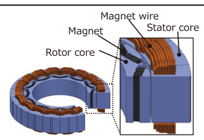
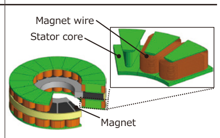
The double-rotor-type motor had a small contact area between the stator and motor housing, making cooling difficult. In contrast, the double-stator-type motor could be constructed so that both stator cores would contact the motor housing over a wider area, thereby allowing the double-stator-type motor coils to be cooled more quickly than the double-rotor-type motor coils. Among motor components, coils raise temperature most significantly. In addition, the double-stator-type motor exhibited a high efficiency in the entire output power range, thereby expanding the rated operation range and allowing the use of a simpler cooling system. Therefore, when the weight of the entire motor system, including the motor cooling system, is taken into account, the superiority of the power density of double-stator-type motors is expected to increase further. At this point, we have only verified this through an electromagnetic analysis. We will also test actual motors to evaluate their performance, including thermal characteristics.

3-2 Design of motors with excellent material and component obtainability

In the preceding section, we described an example of our effort for improving motor output density. This section shows an example of an AFM with the same configuration as that of an RFM used for driving a commercial vehicle. In particular, this example was made from materials and components that are easily available and have a low environmental impact, while taking advantage of the superiority of AFMs and reducing resource risk.[(15),(16)]

Table 3 shows the structure and specifications of the RFM, which was used as a benchmark, together with those of the AFM. The RFM was constructed of an Nd-sintered magnet and rectangular wires. While the Nd-sintered magnet has high magnetic force, it is expensive and involves a resource risk. The rectangular wires help

Table 3. Target specifications of commercial traction motor and designed motor

	RFM	AFM
Schematic illustrations		
No. of pole No. of slot	12pole/18slot	16pole/18slot
Stator core	MSS	SMC (HB2)
Magnet wire	Rectangular wire	Round copper wire
Magnet	Nd sintered	Ferrite sintered
Rotor core	MSS	–
Max. output power	22 kW	
Max. torque	160 Nm	
Max. speed	6800 rpm	
Max. DC-bus voltage	173 V	
Max. inverter current	220 Arms	
Outer diameter	262 mm	
Axial length	79 mm	

increase the space factor. In contrast, the AFM was made from a ferrite magnet, which has low magnetic force but is inexpensive and poses a low resource risk, and round wire having excellent availability. The materials and components used for the AFM are generally unsuitable for improving its output power. However, the use of a core with double pole shoes we developed enabled the AFM to produce output power nearly equal to that of the benchmark RFM, even though both motors had the same shape. Figure 11 shows the efficiency map of each motor. The designed AFM achieved a high efficiency over a wide range, including high-speed rotation range, because of the use of a SMC with low iron loss at high frequencies, a ferrite magnet, and round wires that make it easier to suppress the eddy current loss of the winding. The evaluation results of the actually produced AFM are shown in Fig. 12. We confirmed that this motor demonstrated torque characteristics and motor efficiency nearly equal to the design values.

Due to the characteristics described above, AFMs are also less susceptible to the switching ripple of the inverter and prevent high-frequency waves from lowering motor efficiency. Figure 13 shows the motor efficiency evaluation results after the above effect was taken into account, as well as the evaluation results of fuel efficiency in the WLTC mode composed of the allocation of time used in each running mode close to the actual running of a vehicle. The loss of harmonics-related efficiency of the designed AFM was smaller than that of the benchmark RFM, with approximately 16% less total loss in the WLTC mode.

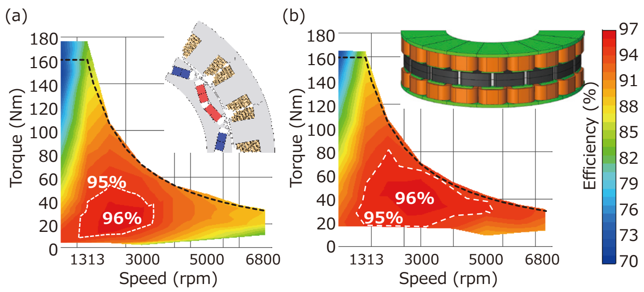


Fig. 11. Efficiency map of (a) commercial traction motor and (b) designed motor

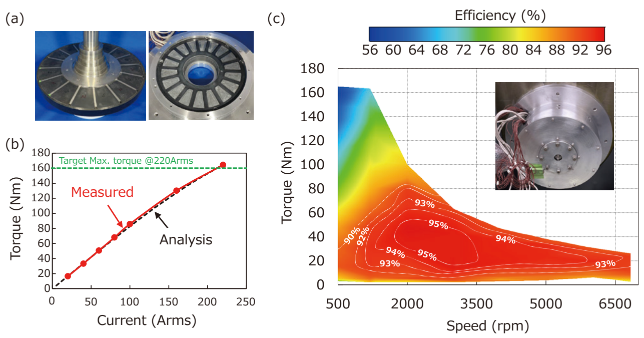


Fig. 12. Torque characteristics and efficiency map of prototype AFM for traction motor application

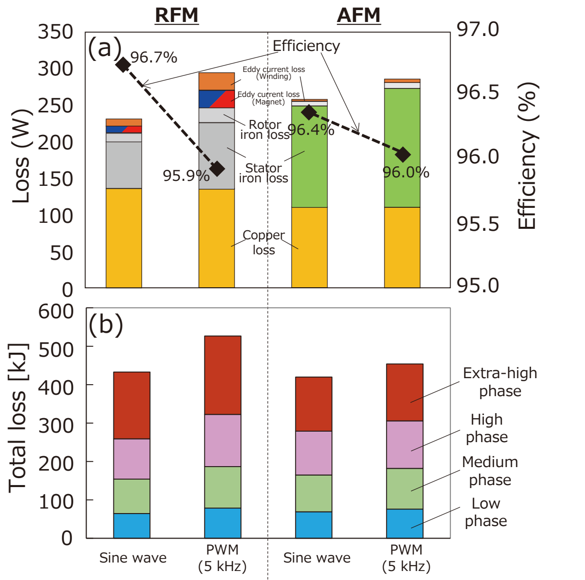


Fig. 13. (a) Comparison in loss and efficiency, and (b) total loss in the WLTC mode under the presence and absence of superimposed harmonics

As described above, the AFM we designed this time saved power consumption during use, which led to a reduction in CO_2 emissions. The AFM is also expected to reduce CO_2 emissions during its production process. Table 4 shows the calculation results of CO_2 emissions during the production process of each motor. As described above, SMCs are more effective in reducing CO_2 emissions than MSSs. Ferrite magnets also emit significantly less CO_2 during the production process than Nd-sintered magnets. These features of SMCs lead to approximately 50% CO_2 emissions reduction by AFMs made from virgin SMCs and 57% CO_2 emissions reduction by AFMs made from SMCs containing recycled powder. The above results verify that AFMs and SMCs are the technology and materials that contribute to the progress of a sustainable society.

Table 4. CO_2 emissions when RFM and AFM are produced[10),(11),(17)]

	RFM				AFM			
	Material	CO_2 emission factor ($kgCO_2$/kg)	Weight (kg)	CO_2 emission (kg)	Material	CO_2 emission factor ($kgCO_2$/kg)	Weight (kg)	CO_2 emission (kg)
Core	MSS	3.7	9.2	34	SMC	0.95 (0.18)	7.2	6.8 (1.4)
Magnet wire	Rectangular copper wire	5.3	3.5	18.6	Round copper wire	5.3	4.9	26.1
Magnet	Nd sintered	27.4	0.9	24.8	Ferrite sintered	2	3	6
Total	–		**13.6**	**77.4**	–		**15.1**	**39.0 (33.6)**

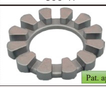
* Numerical values in ( ) represent the emissions when SMCs containing recycled composites are used.

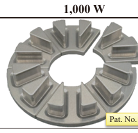
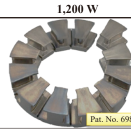
4. Efforts Toward Expanding the Use of AFMs

In the preceding sections, we have verified that AFMs comprising SMCs are effective in enhancing power density and accelerating the progress of a sustainable society. On the other hand, since the social implementation of AFMs is still limited, we have worked on the support of motor manufacturers mainly in 3D electromagnetic analysis, which is considered to be a development barrier, in order to promote further spread of AFMs. Recently, we have begun providing motor developers with samples of our original AFM cores made by molding so that the developers can easily make trial AFMs and evaluate their performance (Table 5).

Furthermore, we have developed trial AFM models that make it easy for motor developers and users interested in AFMs to consider their use. We worked to reduce the thickness of the models to about half that of relatively flat commercial RFMs with the same frame size and output power. In the past, RFMs and AFMs used to be compared in terms of only electromagnetic characteristics. For the trial models, we designed their entire structure with downsizing and improving heat dissipation in mind.[18] In particular, we used the insulation coating technology we developed to achieve the above purposes and adopted uniquely shaped cores, and we demonstrated that the fabricated models have the size and rated power shown in Figs. 14 and 15. Through the above development, we will understand the issues with AFM from the prespective of motor developers, thereby improving our ability to make proposals and leading to the expansion of the social implementation of AFM and SMCs.

Table 5. AFM core samples that can be provided

Power (Typical)	100 W	200 W	400 W	600 W
Core	 Pat No. 7157171	 Pat. applied	 Pat. No. 7157171	 Pat. applied
Dimension (mm)	Φ42-57-9 t	Φ49-57-9.9 t	Φ71-45-13.6 t	Φ75-42-10.5 t
Max. height (mm)	15 t	16.5 t	16.7 t	18.7 t
Outer diameter of winding (mm)	Φ49	Φ54	Φ78	Φ85

Power (Typical)	1,000 W	1,000 W	1,200 W
Core	 Pat. No. 6987327	 Pat. No. 6228633	 Pat. No. 6987327
Dimension (mm)	Φ82-45-15.6 t	Φ98-41-17.8 t	Φ98-41-17.8t
Max. height (mm)	*15.6 t only	20 t	*17.8 t only
Outer diameter of winding (mm)	Φ90	Φ110	Φ110/Φ41

*1 The powers in the table are image values of motors with a double stator and Nd-sintered magnet.
*2 Adjustable depending on motor construction, magnet material, core height, motor specifications (speed and so on).

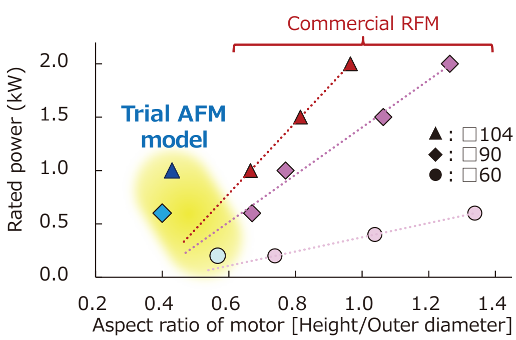


Fig. 14. Lineup of trial AFM model

Fig. 15. Trial AFM model (□90)

5. Conclusion

We have developed new SMCs having excellent performance and recyclability and clarified that their environmental impact is lower than that of MSSs, the mainstream motor core materials at present. In addition, we have described that AFMs made from the developed composites effectively improve the power density and motor efficiency and also reduce CO_2 emissions during the entire motor component production process, thereby contributing to the progress of a sustainable society. To promote the social implementation of AFMs, we have also introduced trial models that will allow motor designers and users to easily experience the benefits of AFMs. We will continue to pursue the development of technologies that will make it possible to improve the performance of AFMs and other types of motors and reduce environmental impact, thereby contributing to the progress of a sustainable society through the continued growth of the motor industry.

6. Acknowledgment

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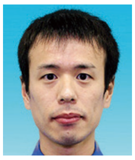
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