Axial-gap Motor Using Thin Wire of Soft-magnetic Pure-iron

Shinya MORITA*1 ・ Takuya MATSUMOTO*2 ・ Shingo KASAI*3

*1 Applied Physics Research Laboratory, Technical Development Group
*2 Applied Physics Research Laboratory, Technical Development Group (currently Japan Superconductor Technology, Inc.)
*3 Wire Rod & Bar Products Unit, Steel & Aluminum Business

Abstract

Since wires of soft-magnetic pure-iron have high magnetic flux densities, they are used for the iron cores of electromagnetic parts for DC-driven components such as electromagnetic relays and solenoids. It has been difficult, however, to apply them to AC-driven components, such as motors, due to the skin effect and eddy current caused in the material. The application to a motor has been examined by decreasing the diameter of the wire of soft-magnetic pure-iron to reduce the eddy current loss. This paper reports the results of a prototype of an axial-gap motor with a new structure using a wound-on iron core of the hexagonal thin wire of pure iron.

Introduction

Addressing global warming and achieving carbon neutrality have recently become pressing issues worldwide. The spread of electric vehicles emitting no CO_2 is also expected to accelerate in the automobile industry. In addition, technological innovations such as Connected, Autonomous, Shared, Electric (CASE) are digitizing and electrifying the drive motors and various components of automobiles, and the diversification of electromagnetic components to meet various needs is expected to continue in the future. A radial-gap motor using a laminated iron core of electrical steel sheets is often used for the onboard auxiliary motor. On the other hand, there is a growing need for miniaturization to accommodate the mounting space of motors, activating the development of an axial-gap motor (AGM) with a structure different from that of the ordinary radial-gap motor. Axial-gap motors are easily made into flat shapes, an advantageous feature for torque enhancement, miniaturization, and weight reduction, and are attracting attention as, for example, in-wheel type motors for directly driving wheels. This paper reports a study on a new AGM using soft-magnetic pure-iron wire with high magnetic flux density and excellent workability. Compared with electrical steel sheets, the soft-magnetic pure-iron wire has fewer impurities and thus a higher magnetic flux density, an advantageous feature for realizing high motor torque in the low rpm region, where the influence of iron loss is minimal. However, the electrical resistance becomes too low if used as bulk, increasing the eddy current loss. Hence, the wire diameter has been reduced to decrease the loss. This paper introduces the exemplary magnetic characteristics of such a soft-magnetic pure-iron thin wire and reports on the motor performance when applied to the AGM's stator iron core, which exploits its high magnetic flux density.

1. Study on motors using soft-magnetic pure-iron thin wire

1.1 Soft-magnetic pure-iron thin wire

Kobe Steel manufactures the soft-magnetic pure iron ELCH2 series, which is widely used in automotive parts such as electromagnetic relays and solenoid iron cores.[1), 2)] The ELCH2 has excellent magnetic characteristics such as high magnetic flux density and low coercive force and is expected to contribute to the effects of miniaturization, weight reduction, low power consumption, and improved responsiveness of "particularly" DC-driven electromagnetic components. On the other hand, it is essential for motors to reduce the iron loss generated in the magnetic body by the AC-magnetic field. As shown in Equation (1), the eddy current loss, which is a part of the iron loss, is proportional to the square of the wire diameter of the material, and it is necessary to use a thinner wire to reduce the eddy current loss;

$$P_v \propto (fB_m d)^2/\rho \quad \cdots\cdots (1)$$

wherein P_v is the eddy current loss, f is the frequency, B_m is the magnetic flux density amplitude, d is the magnetic material diameter, and ρ is the electrical resistivity of the magnetic body.

Generally, thin metal wires are manufactured by cold wire drawing using dedicated dies. The pure iron-based soft magnetic materials are soft and have excellent cold workability, which enables the fabrication of a shape with a regular hexagon as cross-section, facilitating an increase in the space factor.

Fig. 1 and **Table 1** show the AC-magnetization curves (frequency 50 Hz) and iron loss measurements of two types of soft-magnetic pure-iron thin wires with different wire diameters. The figure and table also include examples of the magnetic characteristics of non-oriented electrical steel sheets, 35A300 and 50A600, specified in JIS C 2552. The soft-magnetic pure-iron thin wires have cross-sectional shapes of regular hexagons with opposite sides of 1.24 mm and 0.71 mm, respectively. Kobe Steel's ELCH2 has been cold-drawn to specified wire sizes and heat-treated in a reducing atmosphere to improve their magnetic characteristics. Although the iron loss is slightly higher than that of electrical steel sheet, the pure-iron thin wires are characterized by high saturation magnetic flux densities thanks to the low level of impurities and are suitable for the motors used in the low-rotation, high-torque range where high magnetic flux density is required.

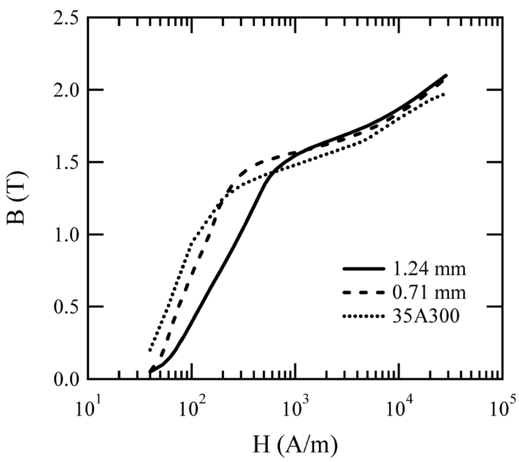


Fig. 1 B-H curves of pure iron hexagonal thin wires

1.2 Design of axial-gap motors

To increase the torque ratio of a motor, it should desirably have a flat shape, in which the torque generating part (the gap between the stator and the rotor) is placed as far outside the rotating body as possible. As shown in **Fig. 2**, a radial-gap motor has a torque generating part placed inside the stator, whereas an AGM has the same located at the outermost part of the iron core and is advantageous for high torque. On the other hand, AGMs have manufacturing issues. For example, there is a report referring to an AGM with a fixed iron core formed by winding and laminating electromagnetic steel sheets in a doughnut shape and then cutting them into a fan shape,[3] but its yield is poor, and the magnetic properties may deteriorate due to the bending. A thin wire could merely be wound and cut to be used as an iron core. Hence, an AGM using pure-iron thin wire has been designed on the basis of electromagnetic field analysis so that it would have the same rating as an auxiliary radial-gap motor commercially available for automobiles. Fig. 2 compares the newly designed AGM with the radial-gap motor reference. The AGM comprises two rotors

Table 1 Example of magnetic properties of pure iron hexagonal thin wires

Material	Magnetic flux density (T)			Iron loss (W/kg)
	B_{25} 2,500 A/m	B_{50} 5,000 A/m	B_{100} 10,000 A/m	$W_{15/50}$ 1.5 T / 50 Hz
Pure iron hexagonal thin wire (d=1.24 mm)	1.65	1.75	1.87	11
Pure iron hexagonal thin wire (d=0.71 mm)	1.63	1.71	1.84	5.35
35A300 (JIS)	> 1.49	> 1.60	> 1.70	<3.0
50A600 (JIS)	> 1.57	> 1.66	> 1.76	<6.0

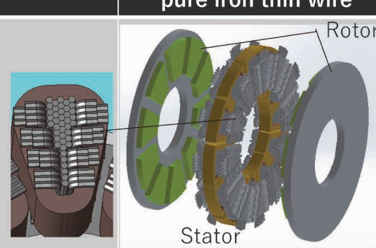
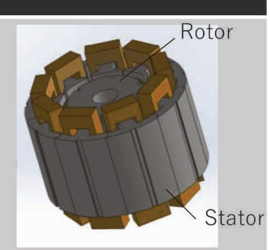
	Axial gap motor using pure iron thin wire	Radial gap motor
CAD model		
Motor type	Axial gap type (2 Rotor, 1 Stator)	Radial gap type
Poles / slots	10 poles/ 12 slots	6 poles / 9 slots
Core size	Φ 101 x 37 mm	Φ82 x 70 mm
Core volume	296 cm^3 (-20% downsized)	370 cm^3
Weight	1.41 kg	1.68 kg

Fig. 2 Specifications of the axial gap motor and a commercial radial gap motor

and one stator, configuring ten poles and twelve slots, in which neodymium magnets, "N42SH", are used for the rotor poles. The air gap between the rotor and stator is 1 mm. The rated rotational speed is 1,080 rpm, the rated torque is 1.3 Nm, and the rated output is approximately 150 W, roughly the same as the output of the commercial motor. The iron core volume of the commercial motor is 370 cm^3, while that of the prototype AGM is 296 cm^3, designed to be 20% more compact. The weight, including the casing, is 1.68 kg for the commercial motor, while that of the prototype AGM is 1.41 kg, a weight reduction of 15%.

1.3 Prototyping of axial-gap motor

Fig. 3 shows a photograph of the prototype AGM stator. The AGM stator uses 85 pure-iron hexagonal wires, each with an opposing side's length of 1.24 mm per tooth. The wires have been magnetic annealed before winding to enhance the magnetic characteristics. The thin wires near the center of the iron core are straight, but each thin wire from the outermost layer to the second layer is bent into a U-shape. This increases the facing area between the stator iron core and the rotor magnet, gains the flux content between the stator and rotor, and enhances the torque. This structure is also advantageous in facilitating the fixing of the coil.

1.4 Electromagnetic field analysis of motor and apparatus for evaluating on actual machine

For the motor design, FEM analysis was performed in advance using the commercially available electromagnetic field analysis software JMAG (ver. 20, registered trademark of JSOL Corporation). The fine wire iron core of the stator has a complicated shape, making the CAD modeling challenging and requiring a significant computational load. Hence, a simplified model was used. The simplified model was made into a bulk shape slightly larger than the actual iron core to

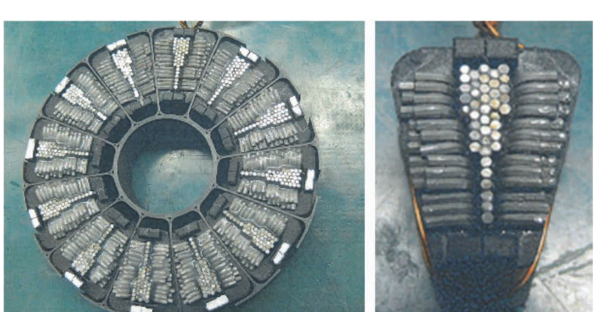


Fig. 3 Photograph of the axial gap motor

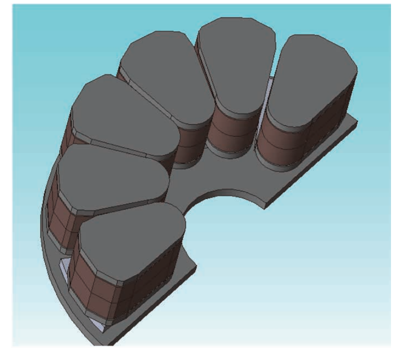


Fig. 4 Bulk core model of the AGM for FEM simulation

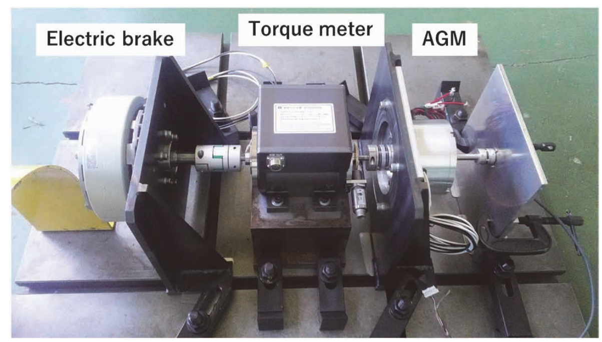


Fig. 5 System for measuring motor properties

enclose the fine-wire iron core, and the space factor of the iron core was adjusted to make the material weight equal to that of the actual machine (**Fig. 4**).

The prototype motor was evaluated using a motor evaluation apparatus in which a Mitsubishi Electric powder brake ZKB-5XN and a torque meter were coupled coaxially, as shown in **Fig. 5**. A MyWay PE-INVERTER was used to control the prototype motor, and a HIOKI power analyzer 3390 was used to obtain efficiency maps in the torque range from 0.3 to 1.6 Nm and the number of rotations from 600 to 1,600 rpm.

2. Evaluation results for prototype motor on actual machine and verification of analysis results

2.1 Evaluation results for prototype motor on actual machine

Fig. 6 shows the results of the AGM's efficiency map measurement. Operating point A represents a point near the rated value of the reference motor (1,000 rpm, 1.3 Nm), operating point B represents a point of high-torque and low-rotation (800 rpm, 1.5 Nm), operating point C represents a point of low-torque and high-rotation (1,600 rpm, 0.6 Nm) and operating point D represents a point of high-torque and high-rotation (1,600 rpm, 1.6 Nm). The motor efficiency is especially high in the high torque range, and the maximum efficiency of 79.8% has been

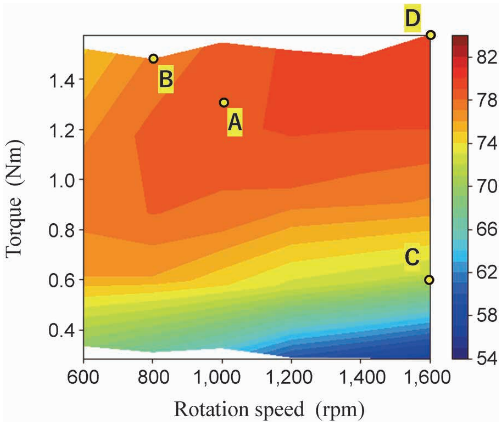


Fig. 6 Efficiency of the axial gap motor

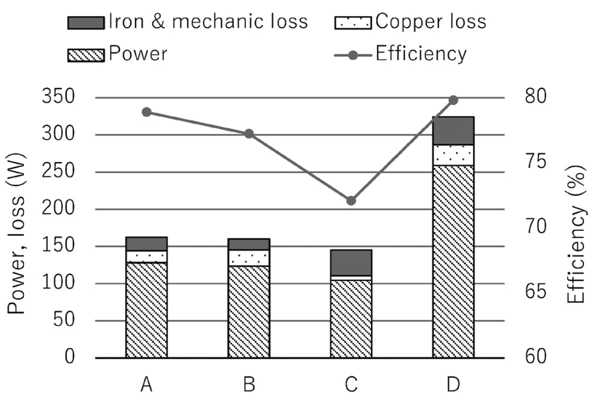


Fig. 7 Motor power and loss at each operating point

confirmed at point D, which is the maximum torque and maximum rotational speed in the measured range. The efficiency at point A near the rated value is 78.9%, which is approximately 2.5 points lower than 81.4% of the reference radial-gap motor. Also, the efficiency of AGM is lower than the value designed by electromagnetic field analysis. The material's magnetic properties were possibly affected by the iron-core processing and assembly of the motor. Hence, optimizing the motor manufacturing method and reducing the wire diameter will realize performance comparable to commercial motors.

Fig. 7 shows motor output, copper loss, mechanic loss + iron loss (calculated by subtracting copper loss from input power) at operating points A to D on the efficiency map. Points A to C are all operating points with an input power of about 150 W. Compared to point C, with low-torque and high-rotation, points A and B on the high-torque and low-rotation sides have improved efficiency. As for the breakdown of loss, the iron loss ratio is high at point C, while the copper loss ratio is higher at points A and B than at point C. Generally, the iron loss depends on the number of rotations and increases on the high rotation side, and the copper loss increases on the high torque side because it is proportional to the square of the current. The prototype AGM reduces the current required for torque output by using a thin pure-iron wire with a high magnetic flux density. From reference points A to C, this AGM is concluded to have a feature of high efficiency even in the high torque range where copper loss is dominant.

2.2 Comparison with electromagnetic field analysis results

Fig. 8 shows the AGM's motor efficiency calculated by electromagnetic field analysis. Similar to the evaluation results on the actual machine, the motor efficiency increases with increasing rotation speeds and torque beyond the range of Fig. 8. For example, the highest efficiency point for 1,600 rpm and 1.6 Nm is 82.6%. The efficiency determined by the electromagnetic field analysis is 3 to 10% higher than that measured on the actual machine in all areas. Possible reasons for this include the effect of mechanical loss, not considered in the analysis, the approximation of the fine wire iron core as a bulk shape, and the effect of increased iron loss in the bent part.

Fig. 9 shows the relationship between the torque

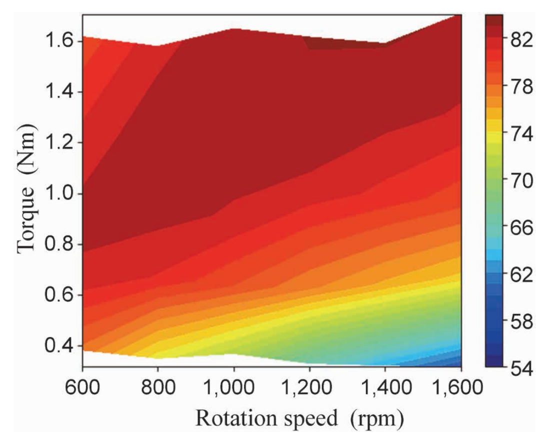


Fig. 8 Motor efficiency calculated by FEM simulation

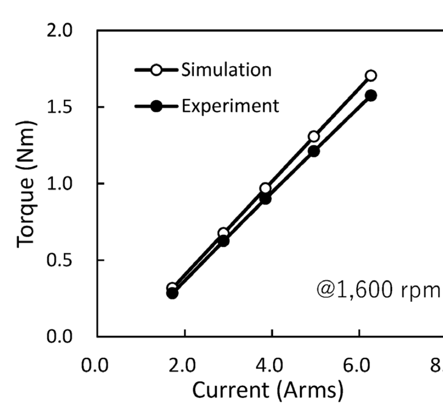


Fig. 9 Comparison of experimental and simulation data for torque current property at 1,600 rpm

and effective current value at 1,600 rpm. Fig. 9 shows the results of both the electromagnetic field analysis and the actual machine evaluation. Although the electromagnetic field analysis results show slightly higher torque, the error is within 10%, and the model approximating a fine iron core to a bulk shape should allow the rough design of a motor with thin hexagonal wire. On the other hand, the bulk model has teeth significantly different from that of the bent fine wire. Hence, tuning the shape and space factor should lead to a design with higher accuracy.

2.3 Effect of thin-wire diameter

The prototype motor has a large iron loss ratio in the high rpm range. Therefore, reducing the iron loss of the fine wire is expected to improve efficiency. As shown in Fig. 1, the thin wire with 0.71 mm opposing sides has lower iron loss and magnetic characteristics better than the thin wire with 1.24 mm opposing sides used in the prototype. Hence, electromagnetic field analysis was performed on the motor characteristics when the magnetic characteristics of 0.71 mm thin wire were applied to the analysis model in section 2.2 to investigate the effects of material properties. **Fig.10** compares the torque, efficiency, and iron loss at a rotational speed of 1,600 rpm, effective current value of 6.3 A (torque 1.6 Nm), i.e., the highest efficiency point in the actual machine evaluation (iron loss in the experimental results includes mechanical loss). Reducing the wire diameter from 1.24 mm to 0.71 mm has improved efficiency by 6 points, increased torque by 6%, and reduced the iron loss of the motor iron core by 58%. The electromagnetic field analysis indicates that the maximum magnetic flux density at the center of the iron core is approximately 1.5 T, and the 0.71 mm wire has excellent magnetic characteristics below 1.5 T (Fig. 1), which is believed to have improved the motor performance. Pure iron has excellent workability, which facilitates the thinning of the diameter. A smaller diameter and higher space factor are expected to result in higher motor torque with higher efficiency.

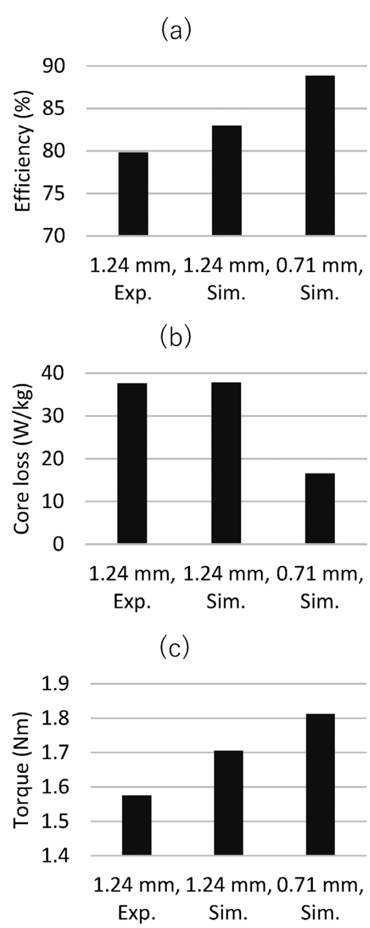


Fig.10 Simulation results of (a) motor efficiency, (b) iron loss and (c) torque for the axial gap motor (1,600 rpm, I_{rms}=6.3 A)

Conclusions

Reducing the diameter of pure iron-based soft magnetic material decreases iron loss. Applying such thin magnetic wire to the stator iron core of an axial-gap motor can reduce its size and weight. The pure-iron thin wire with a high magnetic flux density is expected to lead to enhanced torque, miniaturization, and weight reduction of the motor and is also suitable for, to give an example, a direct drive without a speed reducer. The motor introduced in this paper is merely an example of utilizing pure-iron thin wire. Kobe Steel will continue to contribute to the improved performance of electromagnetic components by devising unprecedented structures and manufacturing methods.

References

1) M. Chiba et al. R&D Kobe Steel Engineering Reports. 2002, Vol.52, No.3, pp.66-69.
2) M. Sakata et al. R&D Kobe Steel Engineering Reports. 2015, Vol.65, No.2, pp.6-11.
3) N. Matsui. Rare earth-saving/No rare earth motors. NIKKAN KOGYO SHIMBUN, LTD. 2013.