Experimental Evaluation of Switched Reluctance Motor Made by Blanking Amorphous Alloy Foil

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This study reveals the characteristics of switched reluctance motors (SRMs) made by blanking (a) 20HX1300 of high grade low-iron-loss silicon steel (0.20mm thickness) and (b) 2605SA1 of amorphous alloy (0.025mm thickness). The blanking of the amorphous alloy is an innovative technology for the mass production of the high efficiency amorphous-alloy-motor. The impact of the processing methods on the magnetic properties are evaluated using the ring cores processed by the following methods: the wire cutting and the blanking. On the other hand, the experiment with the SRMs processed by the blanking evaluates the characteristics depending on the material. As first prototype, 70W-SRM (40mm thickness) is manufactured by blanking 1600 sheets of the amorphous alloy and adhesively laminating them. In the experiment, the motor efficiency of the amorphous-alloy-SRM is improved by 6.9 p.t. compared with that of silicon-steel-SRM. In addition, the iron loss of amorphous-alloy-SRM is reduced by 78.7% compared with that of silicon-steel-SRM.

Keywords : Switched reluctance motor (SRM), ring core, finite element analysis (FEA), amorphous alloy foil, blanking, iron loss

1. Introduction

High-efficiency motor and high-power density motor for home appliances, industrial application, and electric vehicles have been actively studied and developed due to an increasing awareness of environmental issues [1-5]. The electric motor is operated at higher speed in order to achieve the higher power density. High speed operation has become easier with the practical use of wide bandgap semiconductors such as a silicon carbide (SiC) and a gallium nitride (GaN). However, high speed operation deteriorates the motor efficiency due to the iron loss which is increased depending on the electrical frequency. Amorphous alloy has drawn much attentions thanks to its low iron loss properties. In the amorphous alloy, the eddy current loss is small because it is thin and high electrical resistivity. In addition, the hysteresis loss is also small because it has no crystal structure [6]. So far, there are many researches to apply the amorphous alloy into the core of classic motors such as a permanent magnetic synchronous motor (PMSM) [7-11], an induction motor (IM) [12], and a switched reluctance motor (SRM) [13-15]. In particular, Ref.[15] has reported that the iron loss of motor core was reduced by about 80% compared with 35A300 of a general low-iron-loss silicon steel with the employment of amorphous alloy. In addition, the efficiency of this amorphous alloy motor achieved more than 95% at an output of about 2kW thanks to its low iron loss properties. However, wire electrical discharge machining (WEDM), laser cutting, or chemical etching is adopted as a cutting method of the amorphous alloy foil due to the difficulty in machining amorphous alloy. These cutting processes lead to increasing of manufacturing cost and become an obstacle of mass production of an amorphous alloy motor. As the researches for the mass production of the amorphous alloy motor, there are two different approaches; (i) improvement of motor structure in order to avoid the complicated cutting process or (ii) improvement of blanking technology. In approach (i), the simplification of the motor structure has been studied for avoidance of complicated cutting process. Ref.[16-23] have focused on an axial-gap motor whose stator core is a cylinder with a uniform cross-section shape in the axial direction, where it is comparatively easy to manufacture with the amorphous alloy. In particular, Ref.[22] has already commercialized the amorphous alloy axial-gap motor which satisfies the IE4 efficiency class. In addition, IE5 efficiency class is achieved with the improved amorphous alloy axial-gap motor in Ref.[23]. However, these approaches still limit the applicability of the amorphous alloy.

In approach (ii), the cutting of the amorphous alloy foil has been attempted with the development of mold processing machines and technologies [24-30]. Ref.[28] has been reported that amorphous

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1
evaluated with motor. Generally, the evaluation of iron losses is performed using ring cores as a preliminary step in the evaluation of the characteristics of the cores made by different materials and processing methods. The results of experiments at 10000 r/min were compared with those at 7200 r/min to determine the impact of the processing methods on the characteristics of the cores made by different materials and processing methods.

In this paper, an entire switched reluctance motor (SRM) is manufactured using the blanking process to evaluate the characteristics of the cores made by different materials and processing methods. Two ring cores were manufactured using the laser cutting method, and the lamination factors were evaluated to determine the impact of the blanking process on the characteristics of the entire motor. The manuscript also evaluates the B-H characteristics and the iron loss characteristics of the core as a preliminary step in the experimental evaluation of the iron loss characteristics of the entire motor by blanking amorphous alloy foil. In this study, a switched reluctance machine (SRM) was designed and manufactured using amorphous alloy foil.

### Table 1. Specifications of ring-cores

| Name of Ring core | SS-C | SS-B | AA-C | AA-B |
|------------------|------|------|------|------|
| Iron core        | Silicon steel (20HX1300) | Amorphous alloy (2605SA1) |
| Steel Thickness  | 0.20mm | 0.025mm |
| Processing Method| Wire cut* | Laminated | Wire cut* | Laminated |
| Lamination factor| 95.9% | 96.9% | 93.1% | 90.8% |

* The conductive elements of wire cut surface are removed with etching process.

**Fig. 1. Photograph of ring-cores made with the processing methods as shown in Table 1.**

**Fig. 2. Diagrams of measurement setup for ring-core.**

The B-H characteristics and iron loss characteristics of the cores are evaluated using silicon steel and amorphous alloy. The magnetic flux density $B(t)$ and the magnetizing force $H(t)$ are expressed as:

$$B(t) = \frac{1}{N_2 S_c} \int_0^t v_2(t) dt$$

$$H(t) = \frac{N_i(t)}{I}$$

where $v_2(t)$ is the voltage of the secondary winding, $N_i(t)$ is the number of turns in the primary winding, $S_c$ is the effective cross-sectional area of the ring core, $i(t)$ is the current in the primary winding, and $I$ is the effective magnetic path length of the ring core. On the other hand, the iron loss $W$ and the amplitude of magnetic flux density $B_m$ are expressed as:

$}\text{where } m \text{ is the mass of the ring core, } \rho_m \text{ is the density of the material,}$
Therefore, the amorphous alloy has slightly lower magnetic flux density and higher permeability compared with the silicon steel. $B_{hys}$ of SS-B and AA-B are decreased by only 1.3% and 0.3% respectively compared with that of SS-C and AA-C in regard to the difference in the characteristics depending on the processing process. In addition, $\mu_s$ of SS-B and AA-B are decreased by 40.0% and 19.1% respectively compared with that of SS-C and AA-C. Therefore, the blanking process has little effect on the magnetic flux density, but it decreases the permeability. This decrease of the permeability will be due to the properties degradation with plastic strain and elastic strain generated at the end of the steel sheet during the blanking processes. However, $\mu_s$ of AA-B is still same level as that of SS-C in spite of the properties degradation.

### 2.2 Measurement results of B-H characteristic

Fig. 3 shows the measured B-H characteristics, whereas Table 2 shows the magnetic flux density at 7500A/m (which is defined as $B_{75}$) and the permeability around 0A/m (which is defined as $\mu_i$). The frequency of the applied sinusoidal voltage is low frequency of 50Hz in order to avoid the effects of the eddy current loss. $B_{hys}$ of AA-C and AA-B are 10.8% and 9.9% lower than that of SS-C and SS-B respectively in regard to the difference in the characteristics depending on the material. In addition, $\mu_s$ of AA-C and AA-B are 23.6% and 66.7% higher than that of SS-C and SS-B respectively.

![Graph of Magnetic flux density B (T) vs. Magnetizing force H (A/m)](image)

**Table 2. Magnetic flux density at 7500A/m and permeability around 0A/m**

|        | $B_{75}$ (at 7500A/m) | $\mu_i$ (dB/dH around 0A/m) |
|--------|-----------------------|-----------------------------|
| SS-C   | 1.738T                | 0.0195H/m                   |
| SS-B   | 1.715T                | 0.0117H/m                   |
| AA-C   | 1.551T                | 0.0241H/m                   |
| AA-B   | 1.546T                | 0.0219H/m                   |

Therefore, the Steinmetz equation is expressed as

$$W_f = \frac{1}{T_v} \int_0^T v_2(f) dt \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdOTS
calculated as the intercept and slope of $W_i/f$ at $B_m = 1$T as shown in Fig.4. $K_{eddy}$ of AA-C and AA-B are 87.1% and 91.9% lower than that of SS-C and SS-B respectively in regard to the difference in the characteristics depending on the material. Therefore, the eddy current loss of the amorphous alloy is expected to be 1/10 of the silicon steel at the same $f$ and the same $B_m$. In addition, $K_{hys}$ of AA-C and AA-B are 59.7% and 57.9% lower than that of SS-C and SS-B respectively. Therefore, the hysteresis loss of the amorphous alloy is expected to be less than 1/2 of the silicon steel at the same $f$ and the same $B_m = 1$T (because of $B_m^{SS,C} = B_m^{AA,B}$). $K_{eddy}$ of SS-B is increased by 20.6% compared with that of SS-C, whereas $K_{eddy}$ of AA-B is decreased by 24.1% compared with that of AA-C in regard to the difference in the characteristics depending on the processing process. This will be due to the following two factor; (i) the increase of the eddy current loss due to the remaining conductive elements of the wire cut surface which could not be removed even by etching process in SS-C and AA-C and (ii) the properties degradation with the plastic strain and elastic strain generated at the end of the steel sheet during the blanking processes in SS-B and AA-B. In the silicon steel, the impact of (i) is greater than that of (ii). On the other hand the amorphous alloy, the impact of (i) is smaller than that of (ii). On the other hand, $K_{hys}$ of SS-B and AA-B are increased by 17.9% and 23.0% compared with that of SS-C and AA-C. This will be due to the factor (ii). Therefore, the blanking process has little effect on the eddy current loss, but it increases the hysteresis loss. This increase of the hysteresis loss is a problem in the electrical properties of the blanked material. Note that the eddy current loss dominates the iron loss of the high-speed motor. Therefore, the properties degradation due to blanking the amorphous alloy is not a serious problem in practical use.

3. Improvement of accuracy of iron loss analysis in FEA

It was confirmed that the accuracy of FEA is low in the simple iron loss calculation algorithm based on the iron loss curve [31]. This is because the analysis based on the iron loss curve is not applicable into the complicated magnetic flux waveforms of the SRM. In this paper, the hysteresis loss is analyzed based on Play Model [32-33], whereas the eddy current loss is analyzed by Homogenization method [34-35]. These methods are higher accuracy than that based on the iron loss curve thanks to the consideration of the DC bias characteristics of the hysteresis loss and the skin effect of the eddy current loss [36-37].

3.1 Preparation of Play model based method

Fig.5 shows the measured hysteresis curves of AA-B. The play model is the magnetization model which reproduces any minor loop. The hysteresis loss is calculated from the history of magnetization, i.e. the area of the B-H loop. This method is performed considering the DC bias characteristics of hysteresis loop. It is necessary for Play model to prepare a group of major B-H loops with different amplitude as shown in Fig.5. These B-H loops are measured by the method as explained in Subsection 2.2. The measurement range is from 0.05T to 1.90T for 20HX1300, and from 0.05T to 1.55T for 2605SA1. These measured data were implemented in JMAG Designer.

3.2 Preparation of Homogenization method

Table 4 shows the characteristic of 20HX1300 and 2605SA1. The classical eddy current loss $W_{eddy,clas}$ is calculated from the thickness $d$ and electrical resistivity $\rho$ of the electrical sheet in the homogenization method. The values of $d$ and $\rho$ are the catalog value [38-39] in this paper. This method is performed considering the skin effect of the eddy current loss. Note that the classical eddy current loss calculated by the homogenization method does not include the excess loss such as anomalous eddy current loss. Therefore, the modified coefficient $\kappa$ of the classical eddy current loss is defined as

$$\kappa = \frac{K_{eddy}}{2} \left( \frac{B_m^2}{(\pi d)^2} \right) \frac{6\rho}{f B_m}$$

(7)

where $K_{eddy}$ represents the coefficients of the eddy current loss which does not include the skin effect as explained in Subsection 2.3. The eddy current loss $W_{eddy}$ including the excess loss $W_{eddy,clas}$ is expressed as

$$W_{eddy} = W_{eddy,clas} + W_{eddy,clas} = \kappa W_{eddy,clas}$$

(8)

Therefore, the eddy current loss is calculated by multiplying the analysis value of the classical eddy current loss by the modified coefficient $\kappa$. As shown in Table 4, the $\kappa$ of the blanked silicon steel is 2.40, whereas the $\kappa$ of the blanked amorphous alloy is 29.5. There is a pretty difference between the actual eddy current loss and the eddy current loss calculated by the physical property such as the thickness and electrical resistivity in the blanked amorphous alloy.

4. Design and Manufacture of SRMs

Table 5 shows the specifications of the designed SRMs, whereas Fig.6 shows the photograph of the manufactured amorphous-allow-
SRM. 70W SRMs (40mm thickness) are designed as first prototype. Two motor cores are made by blanking (a) 20HX1300 and (b) 2605SA1, which are referred as “SS-SRM” and “AA-SRM” in this paper. The detail of the employed innovative technology in blanking of the amorphous alloys is found in Ref.[40]. The comparative evaluation of the electrical characteristics of the different blanking technologies will be discussed in a future work. Note that the stator outer diameters of the blanked motor core are 40mm. There are problems of the material availability and the mold precision in order to blank larger motor core. The number of layers of SS-SRM is 200, whereas that of AA-SRM is 1600. These motors are manufactured by adhesively laminating the blanked steel sheets. Since it is difficult to laminate very thin steel sheets of the amorphous alloy with a caulking or a welding, an impregnation lamination is employed. There is a problem of the lower productivity due to the requirement of the manufacturing time for the adhesion process. In order to increase the effect of the iron loss reduction, a relatively high-speed motor is designed. In addition, the coil space is bigger than that of a general design [41] in order to increase the winding diameter. This results in low winding resistance and copper loss reduction. Furthermore, the airgap length is selected in order to achieve the highest efficiency within the mechanical constraint of 0.1 mm.

![Fig. 6. Photograph of 70W-SRM made of blanked amorphous alloy foil.](image)

Fig.7(a) depicts the relationship between the airgap length and the motor loss, whereas Fig.7(b) shows the relationship between the airgap length and the motor efficiency. As shown in Fig.7(a), the large airgap extremely increases the copper loss. This is because the reluctance torque becomes small due to small change of the magnetic resistance with the change of the airgap length. The copper loss of AA-SRM remains almost the same to that of SS-SRM. Therefore, the high efficiency is not expected due to small effect of reducing the motor loss with the low iron loss characteristics of the amorphous alloy. In this paper, the airgap length in both SS-SRM and AA-SRM are selected to be 0.1mm in order to achieve the highest efficiency within the mechanical constraint.

The information about the cost, structural strength, and heat-resistant are described. Note that the main subject of this paper is the evaluation of the electrical characteristics of the motors made by blanking the amorphous alloy. Therefore, the information about the cost and other are described as reference values.

Table 6 shows the cost comparison in the different processing methods excluding the cost of the molds and equipment. The cost reduction by the blanking of the silicon steel in the mass production is expected to be 1/30~1/50 compared with that of the wire cutting. On the other hand, that of the amorphous alloy is expected to be 1/10 due to the larger number of required processing methods.

| Name of motor | SS-SRM | AA-SRM |
|---------------|--------|--------|
| Iron core     | 20HX1300 (high grade silicon steel) | 2605SA1 (amorphous alloy) |
| Number of layers | 200 (cal.) | 1600 (cal.) |
| Processing method | Laminated after Blanking | Laminated after Blanking |
| Output power | 70W | 70W |
| Maximum speed | 10000r/min | 10000r/min |
| Number of phases | 3 | 3 |
| Number of poles | 6 (stator) / 4 (rotor) | 6 (stator) / 4 (rotor) |
| Motor size | 40mm × 40mm | 40mm × 40mm |
| Airgap | 0.1mm | 0.1mm |
| Pole arc | 21deg. (stator) / 31deg. (rotor) | 21deg. (stator) / 31deg. (rotor) |
| Number of turns | 73turns | 73turns |
| Space factor of coil | 34% | 34% |

![Fig. 7. Effect of airgap length](image)

Table 7. Cost comparison of blanking processing in different materials

| Material | Wire cure After Laminated | Amorphous alloy |
|----------|--------------------------|-----------------|
| Silicon steel | K_{SS-M} | K_{SS-M}×2 |
| Amorphous alloy | K_{AA-B} | K_{AA-B}×2 |

| Material price | K_{SS-M} | K_{SS-M}×2 |
| Jig tool costs | K_{SS-J} | K_{SS-J}×3–5 |
| Re-polishing cost | K_{SS-R} | K_{SS-R}×30–50 |
| Assembly cost | K_{SS-A} | K_{SS-A}×30–50 |
sheets and the difficulty of processing of amorphous alloy.

Table 7 shows the cost comparison of blanking processing in the different materials. The material cost of the amorphous alloy is expected to be increased by 2 times compared with that of the silicon steel [42]. In addition, the jig tool cost is expected to be increased by from 3 times to 5 times. This is because the clearance of the jig tool is very small, and the required accuracy of the jig tools is very high. In addition, the re-polishing cost is expected to be increased by from 30 times to 50 times. This is because not only the number of required sheets is larger but also the tensile strength is high in the amorphous alloy. In addition, the assembly cost is expected to be increased by from 30 times to 50 times because of the large number of required sheets, more frequently re-polishing, and the manufacturing time for the adhesion process in the impregnation lamination.

The structural strength of the motor made by blanking the amorphous alloy is higher than that of the silicon steel. This is because the structural strength depends on the hardness of the core. The hardness of the amorphous is approximately 5 times higher than that of the silicon steel. On the other hand, the heat-resistant is expected to be same.

5. Experimental evaluation of SRMs

5.1 Test system configuration

Fig.8 (a) depicts the diagrams of the measurement setup for test motor, whereas Fig.8 (b) shows the photograph of the measurement bench. In particular, the motor efficiency characteristics and the iron loss characteristics of SS-SRM and AA-SRM are experimentally evaluated with the measurement bench. The input electric power and the root-mean-square (RMS) value of the winding current are measured with the power meter (PW3390, accuracy ±0.04%, bandwidth 200kHz, HIOKI), whereas the torque is measured with the torque meter (UTMII-1Nm, accuracy±0.01%, bandwidth1kHz, UNIPULSE). The winding temperature is measured by thermocouple built into the winding.

The motor efficiency \( \eta_m \) is expressed as

\[
\eta_m = \frac{P_m}{P_i} = \frac{T_{out}\omega_m}{P_i} \quad \text{(9),}
\]

where \( P_{out} \) is the shaft output which is calculated as product of the measured torque \( T_{out} \) and the shaft angular velocity \( \omega_m \), whereas \( P_i \) is the input electric power which is measured by the power meter. According to the preliminary verification in Ref.[31], the mechanical loss has large dispersion. In addition, there are individual differences of mechanical loss in SS-SRM and AA-SRM. Therefore, it is impossible for the evaluation with Eq.(9) to make a fair comparison. In order to resolve the above problems, the efficiency \( \eta_m \) regarding the mechanical loss as a part of the shaft output is defined as

\[
\eta_m = \frac{P_{out, m}}{P_m} = \frac{P_{out} + W_m}{P_m} = \frac{T_{out}\omega_m + T_{mech}\omega_m}{P_m} \quad \text{(10),}
\]

where \( P_{out, m} \) is the shaft output when the mechanical loss \( W_m \) is regarded as shaft output. Note that \( W_m \) is the product of the measured torque \( T_{mech} \) and the rotational angular velocity \( \omega_m \) when the DC motor drives the system with no SRM excitation. On the other hand, the iron loss \( W_i \) is calculated by subtracting \( P_{out} \), \( W_m \), and the copper loss \( W_c \) from \( P_m \). Therefore, \( W_i \) is expressed as

\[
W_i = P_m - P_{out} - W_m - W_c
\]

\[
= P_m - T_{out}\omega_m - \sum_{x=1}^{2} R_{(R_{(I_{temp}^2})\omega_m} - T_{mech}\omega_m \quad \text{(11),}
\]

where \( R_{(I_{temp})} \) is the winding resistance of \( x \)-phase respectively at winding temperature \( I_{temp} \), whereas \( I_{MEP} \) is the root-mean-square (RMS) value of the winding current of \( x \)-phase respectively.

5.2 Test procedure

The copper loss (winding resistance) depends on the winding
temperature, whereas the mechanical loss depends on the bearing temperature. In particular, the bearing temperature cannot be measured in this system. Therefore, a warm-up operation is required in order to sufficiently warm the bearing.

Fig. 9 shows the speed and the torque during the experiment (Step1~Step6), whereas Table 8 shows the operation of load motor and test motor at each step. At first, the motor is accelerated by load motor (Step1). Next, the load motor drives the system with no SRM excitation for a long time (Step2). In Step2, the mechanical loss becomes stable thanks to warm-up of bearing. Next, the test motor output the torque by controlling the current to the pulse current with the command amplitude (Step3). In Step3, the efficiency and iron loss are calculated from the average value of the measured value in this section. Finally, the motor is decelerated (Step5) and stop (Step6). The zero point of the torque meter is confirmed in the stopped state (Step6).

5.3 Measured characteristics of SS-SRM and AA-SRM

Fig. 10 shows the motor efficiency characteristics of SS-SRM and AA-SRM at 10000r/min. The mechanical loss is not regarded as a part of the shaft output (Eq. (9)). As shown in Fig. 10(a), the motor efficiency of AA-SRM is improved by 6.9 p.t. compared with that of SS-SRM. The mechanical loss is not regarded as a part of the shaft output (Eq. (9)). As shown in Fig. 10(b), the motor efficiency of AA-SRM is improved by 6.9 p.t. compared with that of SS-SRM.

Fig. 11 shows the comparison results of (a) the copper loss and (b) the iron loss of SS-SRM and AA-SRM. As shown in Fig. 11(a), the copper loss of AA-SRM is reduced by approximately 20% compared with that of SS-SRM. In addition, as shown in Fig. 11(b), the iron loss of AA-SRM is reduced by approximately 75% compared with that of SS-SRM. Note that the increase in the iron loss of AA-SRM decreases at high output, i.e., $W_i / P_{out,m}$ becomes low. This is because the increase of the magnetic density decreases at high output due to the magnetic saturation of the amorphous alloy. In addition, the increase in the iron loss increases at low output, i.e., $W_i / P_{out,m}$ becomes high. In the current hysteresis control with a constant hysteresis width, the iron loss due to the switching of the inverter is almost same, i.e., the influence becomes relatively large in the low output.

Fig. 12 shows the comparison result of motor loss at rated power (70W) at 10000r/min.
Fig. 13. Efficiency characteristics of SS-SRM and AA-SRM in all speed range at 1 p.u. torque.

Fig. 14. Iron loss characteristics of SS-SRM and AA-SRM in all speed range at 1 p.u. torque.

Fig. 15. Comparison results between measurement and FEA in all output range at 10000 r/min.

### 5.4 Comparison results between measurement and FEA

Fig. 15 shows the comparison between the measurement results and the FEA results of the iron losses of (a) SS-SRM and (b) AA-SRM. As shown in Fig. 15, there is an error of approximately 15% between the measurement results and the FEA results in both SS-SRM and AA-SRM. These errors will be due to the accuracy of FEA analysis and the accuracy of measurement results. The characteristics of the blanked SRM is analyzed from the data of the characteristics of the blanked ring cores. However, the impact of the blanking process will not always be the same as that of the ring core, especially in complicated parts such as motor teeth. In addition, the iron loss in measurement results is the value calculated indirectly from other measured values by Eq. (11). However, there are errors in the value calculated iron loss due to the considered loss such as the stray load loss and the AC copper loss.

Fig. 16 shows the separation results of the iron loss of (a) SS-SRM and (b) AA-SRM at rated power (70W). The errors between the measurement results and the FEA results are 15% or less in both SS-SRM and AA-SRM. In SS-SRM, the eddy current loss is 59.9%, whereas the hysteresis loss is 40.1% of 5.77W of the total iron loss. On the other hand, in AA-SRM, the eddy current loss is 25.5%, whereas the hysteresis loss is 74.5% of 1.23W of the total iron loss. Therefore, the eddy current loss dominates the iron loss in SS-SRM, whereas the hysteresis loss dominates the iron loss in AA-SRM. In general, the eddy current loss dominates the iron loss of the general high-speed motor as shown in Fig. 16(a) since the eddy current loss is proportional to the square of the electrical frequency. In the amorphous alloy, the eddy current loss is 1/10 and the hysteresis loss is 1/2 compared with the silicon steel. Therefore, the dominant eddy current loss at high-speed motor is dramatically reduced.
6. Conclusion
This paper provided the characteristics of the ring cores and the switched reluctance motors (SRMs) made by blanking (a) 20HX1300 of the high grade low-iron-loss silicon steel (0.20mm thickness) and (b) 2605SA1 of the amorphous alloy (0.025mm thickness). The blanking of the amorphous alloy is an innovative technology for the mass production of the high efficiency amorphous-alloy-motor. The impacts of the processing methods on the magnetic properties were evaluated with the ring cores processed by two methods: the wire cutting and the blanking. On the other hand, the experiment with the SRMs processed by the blanking evaluated the characteristics depending on the material. As first prototype, 70W-SRM (40mm thickness) was manufactured by blanking 1600 sheets of the amorphous alloy and adhesively laminating them. These experiments reveal the following characteristics of the entire motor by blanking the amorphous alloy:
(i) The amorphous alloy is expected to be 1/10 of the eddy current loss and 1/2 of hysteresis loss compared with the silicon steel according to the measured parameters of Steinmetz equation.
(ii) The hysteresis loss is expected to dominate of the iron loss in the amorphous alloy motor even with the high speed operation.
(iii) The blanking of the amorphous alloy impacts the hysteresis loss rather than the eddy current loss, which is the important factor for the high efficiency with the high speed operation.
(iv) The blanking of the amorphous alloy is expected to increase the hysteresis loss by 23.0% according to the measured parameters of Steinmetz equation, which is not a serious problem in practical use.
(v) The iron loss of the amorphous-alloy-SRM was greatly reduced by compared with that of the silicon-steel-SRM. In addition, the motor efficiency of the amorphous-alloy-SRM is improved compared with that of the silicon-steel-SRM.

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