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Measurement of AC-Magnetic Loss in Permanent Magnets at High Temperature

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Abstract:

Most EV/HEV have adopted Nd-Fe-B sintered magnet having high coercive field strength and remanent flux density. AC-magnetic loss in Nd-Fe-B sintered magnets is relatively large compared to ferrite magnets and other permanent magnets due to low electrical resistivity of Nd-Fe-B sintered magnets and there is a concern that the magnet is demagnetized by heat generated from AC-magnetic loss. The evaluation of the AC-magnetic loss especially at high temperature corresponding to internal environment in the motor during driving is important and the measurement-system for evaluation of the AC-magnetic loss was developed. In this paper, the behavior change of the AC-magnetic loss at high temperature (–200°C) in Nd-Fe-B sintered magnets having various H_{cj} and B_r was presented. They indicated that the behavior is different between each Nd-Fe-B sintered magnet, and that it is difficult to consider the behavior associating the loss with basic magnetic properties in the magnets such as H_{cj} and B_r. Furthermore, it was clarified that it is unable to understand the loss-behavior from the change of classical eddy current loss.

1. Introduction

With increasing importance attached to protection of the global environment, unit production of EV/HEV (electric vehicles/hybrid electric vehicles) with low environmental loads is continuing to increase. In EV/HEV, the motor is the basic module which determines the energy efficiency of the vehicle, and the permanent magnets which are components used in EV/HEV motors are key magnetic materials that govern the energy conversion efficiency of the motor. Against the background of demand for compact size (small radius), high power and high efficiency in the traction motors of EV/HEV, Nd-Fe-B sintered magnets have been adopted for use as motor components, as this type of magnet has high Retentivity and Coercivity even among permanent magnets.

However, there are also issues which are specific to Nd-Fe-B sintered magnets. Because Nd-Fe-B sintered magnets have low electrical resistivity in comparison with other types of permanent magnets such as ferrite magnets, large eddy current loss occurs when the magnet is exposed to the alternating current (AC) magnetic field generated for motor drive. Furthermore, this eddy current loss becomes remarkable due to the effects of the carrier-waveform from the inverter and the slot harmonics caused by the rotating structure of the motor. When the energy loss due to this eddy current is large, the energy loss changes to heat, causing the temperature of the magnet to rise, and demagnetization of the magnet by heat is a concern. Therefore, in technical development of magnets used in EV motor, it is first necessary to measure the loss of the magnet.

Various methods for measuring the loss of permanent magnets have been reported [3–6], but in all of these methods, the evaluation is performed at room temperature.

However, when a motor is driving a vehicle, the internal temperature of the motor is not room temperature. This is because iron loss in the core, copper loss in the coil, mechanical loss by motor rotation and windage loss occur during operation, and the motor generates heat accompanying these various types of loss. As a result, the temperature inside the motor is higher than the ambient temperature, and the magnets in the motor core are exposed to high temperatures in the range of 70°C to 120°C. Therefore, loss evaluations of magnets should be carried out under a high temperature conforming to the high temperature environment during motor drive. However, no examples of actual measurement of the magnetic loss of magnets under high temperature conditions have been reported to date. Against this background, JFE Techno-Research Corporation developed a magnetic loss measurement method for magnets applicable at temperatures up to 200°C.

Although it is well known that the magnetic proper-

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ties of Nd-Fe-B sintered magnets change remarkably depending on temperature, how AC-magnetic loss changes with temperature is not known. In conventional method, Since the AC-magnetic loss ΔW_t of a magnet under a high frequency AC magnetic field consists mainly of eddy current loss ΔW_e, and the electrical resistance of a magnet increases with temperature, it is frequently predicted that AC-magnetic loss will decrease at higher temperatures.

This paper presents a brief description of the thinking and measurement methods for evaluation of AC-magnetic loss in magnets. The temperature dependence of magnetic loss in Nd-Fe-B sintered magnets with different properties is also described, and the behavior of magnetic loss is discussed.

2. AC-Magnetic Loss in Magnets

2.1 AC-Magnetic Loss of Magnets

Chapter 1 described the fact that magnetic loss occurs in the magnets in a motor core during motor drive. This loss is the magnetic loss which is generated when the magnets are affected by the AC magnetic field of the motor, that is, AC-magnetic loss. Generally speaking, AC-magnetic loss can be broadly divided into hysteresis loss and eddy current loss. Eddy current loss is the energy loss accompanying the eddy current generated in a magnet when the magnet is exposed to an external AC magnetic field. On the other hand, although it is also known from previous research[3] that hysteresis loss occurs when an AC magnetic field is applied to a magnet, the mechanism responsible for hysteresis loss under an AC magnetic field has not been clarified.

In this research, we developed a method for evaluating AC-magnetic loss, which is the sum of eddy current loss and hysteresis loss. This evaluation method is explained in the following section.

2.2 Method for Evaluation of AC-Magnetic Loss of Magnets

According to previous research, the AC-magnetic loss of a magnet can be calculated by the following Eq. (1)[5].

$$W_t = \frac{f}{\rho_m} \int HdB \ [\mathrm{W/kg}] \quad \cdots\cdots (1)$$

In Eq. (1), H is the Magnetizing Fore of an external AC magnetic field applied to a magnet, magnetic flux density B is the B of the magnet under the applied AC magnetic field, f is the frequency of the applied AC magnetic field and ρ_m is the density of the magnet. Therefore, it is possible to calculate and evaluate the AC-magnetic loss of a magnet by measuring the H of the applied AC magnetic field, and measuring/calculating the magnetic flux density B of the magnet at that time. The meaning of Eq. (1) as a magnetic phenomenon is described in the next section.

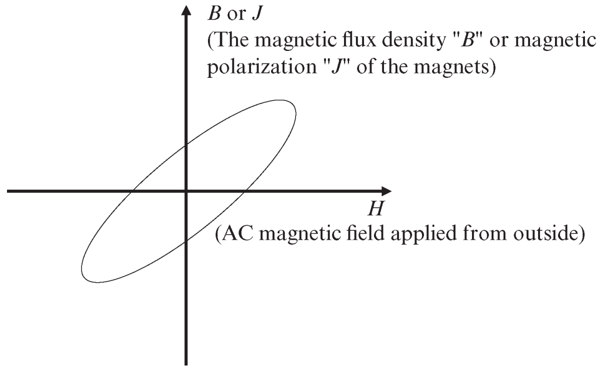

Fig. 1 BH-loop measured by applying AC magnetic field to magnet (AC-minor loop)

2.3 Understanding of Magnetic Phenomenon and AC Minor Loop

We do not completely understand the micro magnetic phenomenon in a magnet when an AC magnetic field is applied, although, this section will briefly describe the phenomena as best as can be understood from Eq. (1). If a direct current (DC) magnetic field is applied to a magnet, the magnet will be magnetized or demagnetized, depending on the direction of the magnetic field, and as a result, the magnetic flux density of the magnet will change. On the other hand, because the magnetizing fore applied in evaluations of AC-magnetic loss is an AC magnetizing fore, in which the direction of the field changes periodically, magnetization and demagnetization do not occur in permanent magnets, which are more difficult to magnetize/demagnetize than soft magnetic materials. **Figure 1** shows the B-H loop when an AC magnetizing fore is applied to a magnet. For convenience, we will call the loop in Fig. 1 the AC-minor loop. When this kind of waveform is obtained, the magnetic flux density B of the magnet vibrates periodically.

The integral term in Eq. (1) is equivalent to the area of this AC-minor loop. This means that AC-magnetic loss changes when the AC minor loop changes, and AC-magnetic loss decreases if the area of the loop decreases.

3. Measurement Method and Experimental Procedure

3.1 Measurement Method

Chapter 2 showed that the AC-magnetic loss of a magnet can be calculated by measuring the *H* of the applied AC magnetizing fore and measuring and calculating the flux density *B* of the magnet at that time. This section introduces a method for actually measuring *H* and *B*. Figures 2 and 3 show schematic diagrams of the measurement systems in the AC magnetizing device used on those measurements. In this measurement system, the sample magnet is placed in the excitation coil, and an AC magnetizing fore is applied to the magnet by the AC magnetizing fore generated by electrification of the coil. The flux density *B* of the magnet is obtained with a detection coil installed around the outer periphery of the magnet. It is also possible to measure magnetic polarization *J* by using a coil that detects *J*. The value of the applied magnetizing fore *H* is acquired with a magnetic field strength detection coil installed around the magnet. These detection coils were prepared by the method reported in previous research[5)].

Now, the difference between **Fig. 2** and **Fig. 3** will be explained. Fig. 2 is a closed magnetic circuit type and Fig. 3 is an open magnetic circuit type. With the closed magnetic circuit type, it is also possible to apply a high magnetizing fore by laying out four yokes in the shape of a circle, which is a closed magnetic circuit. In this case, it is possible to evaluate a magnet under a condition in which a demagnetization field does not exist in the magnet, even when it is magnetized. On the other hand, as shown in Fig. 3, an open magnetic field is formed when there are no yokes around the magnet. In this case, a magnetized magnet can be evaluated under a condition in which a demagnetization field exists in the magnet. The data shown in this paper were evaluated using the open magnetic circuit measurement system shown in Fig. 3.

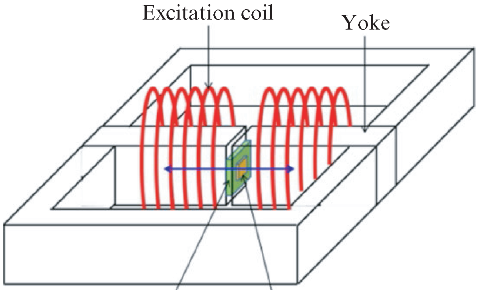

Fig. 2 Diagram of measurement system in AC magnetizing device (Closed magnetic circuit)

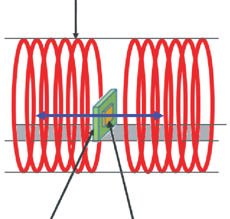

Fig. 3 Diagram of measurement system in AC magnetizing device (Open magnetic circuit)

3.2 Magnets Used in Evaluation

Four types of Nd-Fe-B sintered magnets (Samples #A, #B, #C, #D) with different properties were evaluated. The basic magnetic properties of these magnets are shown in **Table 1**. Samples #A, #B and #C are magnets given surface oxidation treatment, and Sample #D is a nickel-plated magnet. The size of all samples was length 7 mm x width 7 mm x height 7 mm The 7 mm height direction is the easy magnetization direction, and these samples were magnetized in the direction of the axis of easy magnetization. An AC magnetic field was applied in the magnetization direction, and AC-magnetic loss was measured.

3.3 Measurement Conditions

Loss was measured by applying an AC magnetizing fore to the magnet samples with the developed open magnetic circuit measurement system (Fig. 3). Using the AC magnetic field frequency of 1 kHz and the magnetizing fore *H* of ±8 kA/m, AC-magnetic loss was measured from room temperature to approximately 160°C.

3.4 High Temperature Measurement Method

Measurements under high temperatures were carried out by installing the measuring system in Fig. 3 in a constant temperature chamber which is capable of temperature control at high temperatures, as shown in **Photo 1**. To enable high temperature measurements, the measurement system in Fig. 3 consisted of a lead wire

Table 1 Magnetic property of magnets

Sample	B_r (T)	H_{cj} (kA/m)	H_k/H_{cj} (%)	Surface treatment
#A	1.26	1 818	98.5	Oxidation treatment
#B	1.28	1 812	99.0	
#C	1.45	1 114	99.2	
#D	1.22	1 115	97.0	Nickel plating

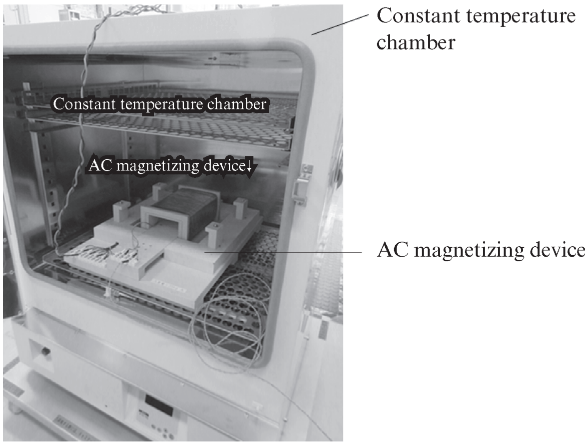

Photo 1 Measurement at high temperature (Open magnetic circuit)

with heat resistance up to about 200°C and a bobbin with heat resistance up to about 500°C. The evaluation error for AC-magnetic loss when using the measurement system in Fig. 3 at high temperatures is ±3% or less.

The heating rate of the constant temperature chamber was set to approximately 0.9°C/min. The measurements were carried out after confirming that the sample temperature had reached the measurement target temperature. Because the sample temperature is 3°C lower than the temperature of the bobbin of the coil, the sample temperature at the time of the loss measurement was calculated by subtracting 3°C from the bobbin side temperature. The temperature of the bobbin composing the coil was measured with a thermocouple attached to the bobbin.

3.5 Measurement of DC Electrical Resistivity

Although the AC-magnetic loss in a magnet consists of hysteresis loss and eddy current loss, according to previous research[3)], the AC-magnetic loss when a magnet is magnetized is considered to be almost entirely eddy current loss (AC-magnetic loss ≒ eddy current loss). Eddy current loss can be divided into classical eddy current loss and abnormal eddy current loss, but following the previous research[3)], the change behavior of AC-magnetic loss depending on temperature was analyzed on the assumption that eddy current loss = classical eddy current loss.

Because the above-mentioned classical eddy current loss is proportional to the square of the magnetic flux density of a magnet and inversely proportional to its DC electrical resistivity[3)], the temperature-dependent change behavior of classical eddy current loss (≒AC-magnetic loss) can be interpreted by investigating the temperature-dependent behavior of changes in the magnetic flux density or DC electrical resistivity of the magnet. Therefore, the temperature dependence of changes in DC electrical resistivity in each magnet was investigated.

The measurements of DC electrical resistivity were carried out by the DC four terminal method using samples with dimensions of length 10 mm x width 15 mm x height 7 mm, except in the case of Sample #D, which had dimensions of length 7 mm x width 7 mm x height 7 mm. In all samples, the 7 mm height direction is the direction of the axis of easy magnetization. The samples were electrified using a lead wire welded to the sample, at that time a current was passed to width-directions. For the high temperature measurements, the sample with the attached lead wire was placed in the constant temperature chamber, and the temperature of the magnet at that time was measured with a thermocouple attached to the bottom side of the magnet. The heating rate of the magnets was set to approximately 0.5°C/min.

4. Measurement Results

4.1 Results of AC-Magnetic Loss Measurements

Figure 4 shows the temperature dependence on the rate of change of AC-magnetic loss in each magnet. In this graph, the vertical axis shows the rate of change of AC-magnetic loss from room temperature, and the horizontal axis shows the temperature of the magnet. The rate of change on the vertical axis ΔW_t was calculated by Eq. (2).

$$\Delta W_t[\%] = \frac{W_{t\,T'} - W_{t\,RT}}{W_{t\,RT}} \times 100 \quad \cdots\cdots (2)$$

$\Delta W_{t\,RT}$: AC-magnetic loss at room temperature
$\Delta W_{t\,T'}$: AC-magnetic loss at an arbitrary temperature from room temperature to 200°C T'

A negative change rate on this vertical axis means a decrease in AC-magnetic loss due to heating, and a positive change means an increase in AC-magnetic loss due to heating. The AC-magnetic losses of Samples #A and #B decreased approximately linearly as the temperature increased. On the other hand, the AC-magnetic loss of Sample #D increased suddenly at around 100°C, while that of Sample #C decreased suddenly at around 130°C. From these results, it was found that Nd-Fe-B sintered magnets with different properties display different temperature dependence of AC-magnetic loss. Moreover, comparing Table 1 and Fig. 4, it was also found that the temperature change behavior of AC-magnetic loss cannot be clearly explained in terms of the relationship with the Coercivity H_{cj},

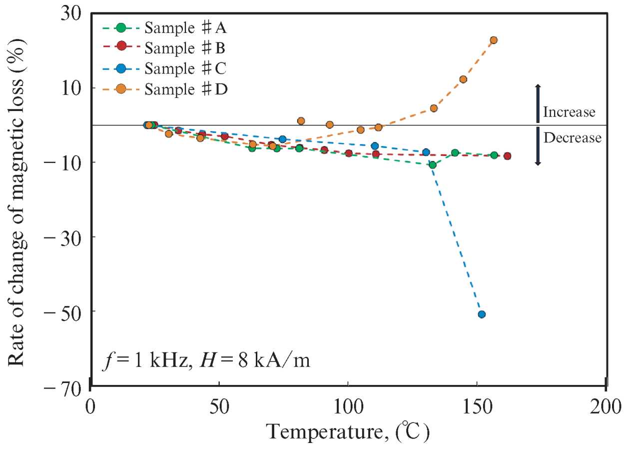

Fig. 4 Change rate of AC-magnetic loss against temperature

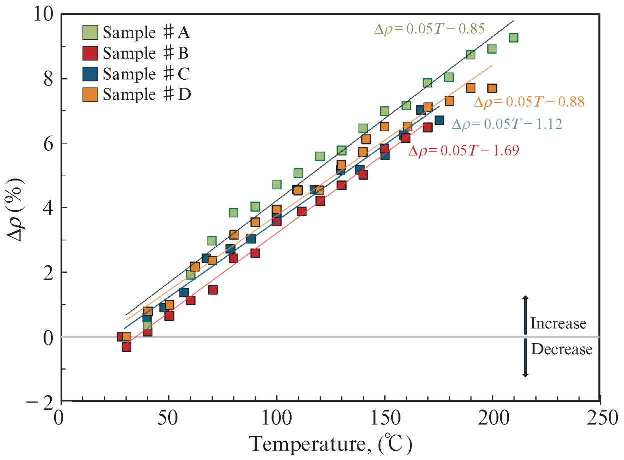

Fig. 5 Change rate of electrical resistance against temperature

Retentivity B_r, or other basic property values.

4.2 Results of DC Electrical Resistivity Measurements

Figure 5 shows the temperature dependence of the DC electrical resistivity of the sample magnets. The vertical axis shows the rate of change of electrical resistivity from room temperature, and the horizontal axis shows the temperature of the magnets. The rate of change of electrical resistivity $\Delta\rho_t$ was calculated by the following Eq. (3).

$$\Delta\rho_t[\%] = \frac{\rho_{t\,T'} - \rho_{t\,RT}}{\rho_{t\,RT}} \times 100 \quad \cdots\cdots\cdots\cdots (3)$$

$\Delta\rho_{t\,RT}$: electrical resistivity at room temperature

$\Delta\rho_{t\,T'}$: electrical resistivity at an arbitrary temperature from room temperature to 200°C T'

A negative rate of change on the vertical axis means a decrease in electrical resistivity due to heating, and a positive rate of change means an increase in electrical resistivity due to heating. As shown in Fig. 5, the electrical resistivity of all magnets showed a similar linear increase, and their slopes as a linear function of temperature and $\Delta\rho$ were the same at approximately 0.05%/°C. Although there were differences in the temperature change behavior of the AC-magnetic loss of each magnet, no remarkable differences were seen in the temperature dependence of electrical resistivity.

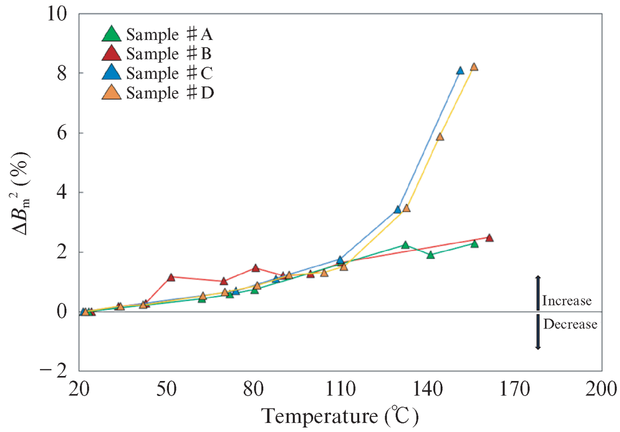

Fig. 6 Change rate of B-amplitude against temperature

4.3 Temperature Dependence of Maximum Amplitude of Flux Density of Magnets

Section 3.5 mentioned that classical eddy current loss is proportional to the square of the flux density of a magnet. **Figure 6** shows the temperature dependence of the square of the flux density of the magnets. The squares of the flux density of the magnets shown here were the squares of the maximum flux density amplitude B_m, B^2_m, of the AC minor loop. In this figure, the vertical axis shows the rate of change of the square of the maximum flux density amplitude from room temperature, and the horizontal axis shows the temperature of the magnets. The rate of change on the vertical axis was calculated by the following Eq. (4).

$$\Delta B_m^2[\%] = \frac{B^2_{m\,T'} - B^2_{m\,RT}}{B^2_{m\,RT}} \times 100 \quad \cdots\cdots\cdots\cdots (4)$$

B^2_{mRT}: square of the maximum magnetic flux density amplitude B_m at room temperature

$B^2_{mT'}$: square of the maximum magnetic flux density amplitude B_m at an arbitrary

temperature from room temperature to 200°C T'

The negative rate of change on the vertical axis means a decrease in the maximum flux density amplitude due to heating, and a positive rate of changes means an increase in the maximum flux density amplitude due to heating. The ΔB^2_m of Samples #A and #B showed a substantially linear increase as the temperature increased, while the B^2_m of Samples #C and #D increased approximately linearly until around 110°C, but then increased dramatically after 110°C.

5. Discussion

AC-magnetic loss W_t comprises eddy current loss W_e and hysteresis loss W_h. Their relationship is as shown in the following Eq. (5)[5].

$$W_t[\mathrm{W/kg}] = W_h[\mathrm{W/kg}] + W_e[\mathrm{W/kg}] = k_h f B^2 + k_e f^2 B^2 \quad \cdots\cdots\cdots (5)$$

f: frequency, B: flux density of magnet
k_h: constant related to hysteresis loss
k_e: constant related to eddy current loss

Based on Eq. (5), when considering the ratio of hysteresis loss W_h and eddy current loss W_e in AC-magnetic loss, the ratio of eddy current loss W_e in total AC-magnetic loss W_t under the frequency condition of 1 kHz in this study is considered to be extremely high (this discussion is based on the premise that k_h cannot be 1 000 times or more larger than k_e). Therefore, based on the results of previous research[3], the temperature-dependent change behavior of AC-magnetic loss was considered only in terms of classical eddy current loss. As mentioned in section 3.5, classical eddy current loss W_e is inversely proportional to electrical resistivity and proportional to the square of flux density. Therefore, the change of AC-magnetic loss with increasing temperature will be discussed assuming the relationship shown in the Eq. (6) below holds, from here.

$$W_t \cong W_e \propto \frac{B_m^2}{\rho} \quad \cdots\cdots\cdots (6)$$

* B of a magnet was defined as the maximum magnetic flux density amplitude B_m.

If the temperature-dependent change of AC-magnetic loss is predicted from Eq. (6), Fig. 5 and Fig. 6, in the case of Samples #A and #B, ρ and B^2_m increase according to the relationship $\Delta\rho \geq \Delta B^2_m$ at all temperatures, so it is predicted that W_t will decrease approximately linearly as the temperature rises. Since this prediction is in agreement with the results in Fig. 4, the behavior of ΔW_t of Samples #A and #B is considered to be determined mostly by the behavior of ΔW_e (this means that $W_t \cong W_e$ at all temperatures). On the other hand, in the case of Samples #C and #D, ρ and B^2_m increase according to the relationship $\Delta\rho \geq \Delta B^2_m$ up to 140°C, but because ΔB^2_m increases dramatically after 110°C, ΔB^2_m exceeds $\Delta\rho$ after 140°C (i.e., $\Delta\rho < \Delta B^2_m$). Therefore, it is predicted that the W_t of Samples #C and #D will decrease up to 140°C, and then increase dramatically after 140°C. However, contrary to this prediction, the results in Fig. 4 show that the W_t of Sample #C decreased dramatically after 130°C. Based on this, the temperature-dependent change behavior of the AC-magnetic loss of Sample #C cannot be considered simply in terms of the relationship in Eq. (6). This means that we cannot predict the change of AC-magnetic loss with temperature based only on the behavior of the change in classical eddy current loss due to heating.

Lastly, the behavior of ΔW_t accompanying temperature rise in Samples #C and #D was considered in terms of the temperature-dependent change of the AC minor loop (the area of the AC minor loop is proportional to ΔW_t). As the AC minor loop, the J-H loop was described because the changes in its shape can be understood easily. J and B have the relationship $B = \mu_0 H + J$. Therefore, when H is constant, as in these measurements, the increase/decrease behavior of J and B is the same. **Figure 7** shows the AC J-H minor loop of Sample #D. As the temperature increases, the maximum magnetic polarization J_m increases, and in particular, J_m increases dramatically after 110°C. However, no remarkable changes were seen in the loop width. It can be understood that the rapid increase in AC-magnetic loss from around 100°C in Sample #D is due to an increase in B^2_m ($\fallingdotseq J^2_m$). On the other hand, **Fig. 8** shows the J-H minor loop of Sample #C, and **Fig. 9**

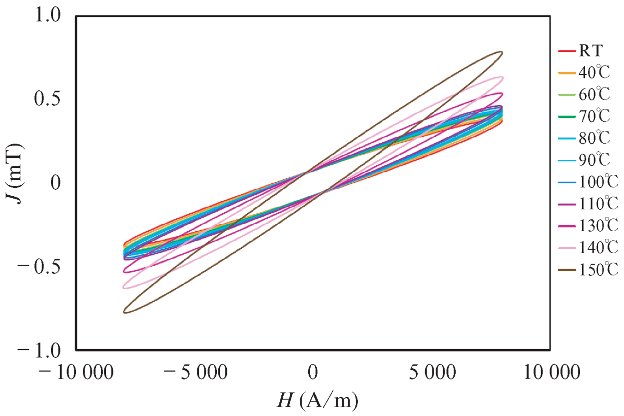

Fig. 7 AC-minor loop in sample #D (J-H loop)

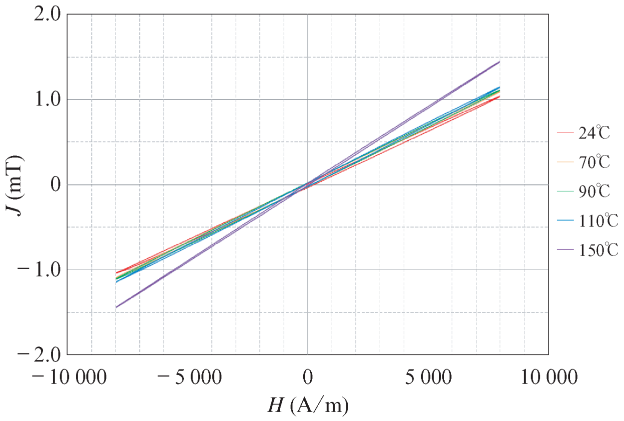

Fig. 8 AC-minor loop in sample #C (J-H loop)

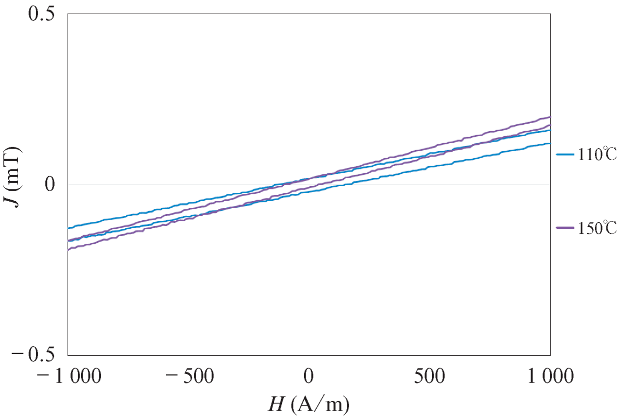

Fig. 9 Enlarged view of AC-minor loop in sample #C

shows an enlargement of Fig. 8 (only for 110˚C and 150˚C). As the temperature increased, J_m showed an increasing tendency, and in particular, J_m increased dramatically at 150˚C (Fig. 8). However, the loop width became narrower at 150˚C (Fig. 9). From this loop behavior, it can be inferred that the dramatic increase in the AC-magnetic loss W_t of Sample #C after 130˚C was due to a decrease in the loop width of the AC-minor loop. In order to understand this decrease, it is important to clarify the relationship of the changes in the shape of the AC-minor loop and AC-magnetic loss W_t, and for this, accumulation of data on AC-magnetic loss under high temperature environments will be essential. Moreover, for a fuller interpretation, elucidation of the temperature-dependent change behavior of hysteresis loss W_h will also be necessary.

6. Conclusions

• It is necessary to understand the AC-magnetic loss of the Nd-Fe-B sintered magnets used in the motors of EV/HEV, because the magnets have low electrical resistivity. Therefore, the evaluation method described below was developed, and this issue was studied based on actual measurements.
• An evaluation method for the AC-magnetic loss of magnets under high temperature environments conforming to the internal environment (70˚C to 120˚C) of EV/HEV motors was developed.
• The magnetic loss of Nd-Fe-B sintered magnets with different basic properties under high temperature environments was measured, and the following conclusions were drawn from the measured data.
• Although all the samples tested were Nd-Fe-B sintered magnets, their AC-magnetic loss showed different temperature-dependent change behavior due to differences in the properties of the magnets.
• This study showed that the change of AC-magnetic loss due to increasing temperature cannot be clearly explained only in terms of basic magnetic properties value such as coercive force H_{cj} and remanent magnetic flux density B_r.
• It was also shown that the change of AC-magnetic loss with increasing temperature cannot be explained only by the temperature dependency of classical eddy current loss behavior (electrical resistivity behavior).

As summarized above, the temperature-dependent change behavior of the AC-magnetic loss of magnets cannot be predicted based only on the conventional understanding, indicating the importance of actual measurement of the changes in AC-magnetic loss with increasing temperature.

Acknowledgement

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