Iron Loss and Hysteresis Properties of an Amorphous Ring Core at High Temperatures under Inverter Excitation

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Several researchers have recently studied high-temperature (HT) motor drive systems under harsh temperature environments. We experimentally and numerically investigate iron loss and the magnetic hysteretic properties of amorphous magnetic materials (AMM) at room temperature (RT) and HT under pulse width modulation (PWM) inverter excitation. We demonstrate that the iron loss of AMM core fed by PWM inverter decreases as temperature increases similar like in the sinusoidal case. In addition, the temperature dependence of the B – H hysteresis curves of AMM under PWM inverter excitation relies not only on major loops but also on minor loops. Because the current at 300 °C is higher than that at RT, the torque of the motor with AMM at HT becomes large at a few operating points. To realize low iron loss of HT motor drive systems, it is important to reduce eddy current losses of AMM cores at HT under PWM inverter excitation compared with the cases at RT. These results facilitate further research in iron loss reduction of motor systems based on studies of magnetic properties at HT under PWM inverter excitation.

Key words: amorphous magnetic materials, high-temperatures, iron loss, hysteresis property, inverter

1 Introduction

Recently, several researchers have studied high-temperature (HT) motor drive systems under harsh temperature environments (e.g. fire sites, aerospace, and automotive)\(^1\)–\(^9\). To perform the speed and torque control of these systems, pulse width modulation (PWM) inverters are commonly used\(^6\)–\(^10\). When the PWM inverter excites the magnetic core used in the motor, the iron losses increase by 10%–50%\(^10\) compared with the case under sinusoidal excitation owing to higher harmonic components. The temperature dependence of iron loss properties of conventional non-oriented (NO) electrical steel sheets (magnetic materials) have been demonstrated\(^4\). In addition, in the previous study\(^4\), there has been no report on the loss repartition properties. To conduct fundamental research to develop high-efficiency motor drive system at HT, it is necessary to figure out magnetic characteristics of amorphous magnetic material (AMM) cores in HT environments under PWM inverter excitation.

To carry out iron loss reduction of the motor core particularly in high-frequency regions\(^4\), a few researchers have studied the motor cores using AMM\(^15\)–\(^20\) that result in low iron losses compared with conventional non-oriented (NO) silicon steel. AMM is a suitable core for high-speed (HS) motor systems\(^21\). Further, in the HS motor system, the core is influenced by temperature. It is important to examine iron loss, hysteresis, and loss repartition (between the eddy current and the hysteresis losses) properties of AMM at HT excited by a PWM inverter.

Based on both experiments and numerical simulations, we examine the iron loss and magnetic hysteretic properties of AMM core at room temperature (RT) and 300 °C (HT) under PWM inverter excitation. This paper reports on the experimental iron loss and hysteretic properties of a ring specimen with AMM under a wide temperature range (RT and HT) condition. Here, the play model with the Cauer circuit\(^1\)–\(^5\),\(^10\)–\(^13\) is used for numerical simulations. We discuss the loss repartition between the eddy current and the hysteresis losses at RT (about 27 °C) and 300 °C.

2 Experimental and Numerical Methods

Figure 1 shows the experimental system employed to measure the iron loss properties of a ring specimen with AMM (SA1) under a wide temperature range condition. The AMM alloy ribbons are laminated and then impregnated with acrylic resin to fabricate a block core. This laminated block core is cut in the shape of a ring core. The AMM ring core with an outer and inner diameter of 102 mm and 127 mm, respectively, is constructed. The space factor $\varepsilon_{sf}$ of the AMM core is approximately 93.5 %. The primary and secondary coils are wound into the ring core. The ring specimen with AMM is set in the oven to examine temperature dependence of iron loss properties. In this study, this ring specimen with AMM is set to either RT or 300 °C. More details of the ring specimen can be found in Ref.\(^25\).

Here, we measure iron loss characteristics of the AMM ring specimen at RT and HT excited by a PWM inverter (MWINV-9R122C, Myway). The iron loss $W_{\text{ring}}$ of the ring specimen with

Fig. 1 Schematic of iron loss measurement system of AMM ring specimen excited by PWM inverter.
AMM is described by\(^4,5\)
\[
W_{\text{ring}} = \frac{1}{T_p} \int H \, dB, \tag{1}
\]
where \(H\) denotes the magnetic field intensity, \(B\) is the magnetic flux density, \(T = 0.02\) s is the period, and \(\rho = 7180 \, \text{kg/m}^3\) is the density of AMM. Here, \(H\) and \(B\) are represented as \(N_1 I / l\) and \(\int \mathcal{V} dt / (N_2 S E_d)\), respectively, where \(N_1 = 103\) denotes the number of turns in the exciting coil, \(l\) is the current flowing in the primary coil of the ring core, \(I = 0.36\) m is the magnetic path length, \(V\) is the voltage of the secondary coil, \(N_2 = 103\) is the number of turns of the secondary coil, and \(S = 87.5 \, \text{mm}^2\) is the cross-sectional area of the ring core. The primary and the secondary windings are set to have the same number of turns because it is important to measure higher harmonic (small voltage) waves and to suppress the measurement error of the magnetic flux density.

In this study, to simulate numerical \(B - H\) hysteresis curves of the ring specimen fed by a PWM inverter under a wide temperature range (RT and HT) condition, we use the play model with the Cauer circuit as a dynamic hysteresis model (See Refs.\(^4,5,32,33\)) for details regarding the play model with the Cauer circuit.). The \(B - H\) hysteresis curve in the play model with the Cauer circuit is given by\(^4,5,32\)
\[
H_{\text{DC}}(B) = H_{\text{DC}}(B) + \frac{7(B^2 - B^{-1}) + 2L h_2^{-1}}{7R_E \Delta t + 2L} + \frac{3L (h_2^2 - h_2^{-1})}{35R_E \Delta t}, \tag{2}
\]
\[
R_E = \frac{12}{\alpha \sigma d^2}, \tag{3}
\]
where \(H_{\text{DC}}(B)\) denotes the DC hysteresis curve calculated by the play model, \(\sigma\) is the electrical conductivity of AMM, \(\Delta t\) is the time division, \(d\) is the thickness of AMM, \(k\) is the step number, \(R_E\) is the resistance to express eddy currents, \(L\) is the equivalent inductance to represent the magnetic flux caused by eddy currents, and \(\alpha\) is the anomaly factor to represent anomalous eddy currents. Here, \(L\) and \(\alpha\) are fitting parameters. In our study, by adjusting \(L\), the numerical iron loss of the minor loop is fitted to the measured loss. Then, \(\alpha\) is adjusted to equalize the numerical loss to the experimental one.

In our numerical simulations, \(L\) at the carrier frequencies of 1, 5, 10, 15, and 20 kHz is obtained as about 10, 4, 2, 0.8, and 0.4 mH, respectively, (8, 3, 1, 0.6, and 0.4 mH) at RT (300 °C). It is thought that the ratio of iron loss based on \(L\) in the minor loops changes as temperature increases. \(\alpha\) at \(f_c = 1, 5, 10, 15,\) and 20 kHz is about 278, 274, 260, 255, and 253 at RT (202, 200, 199, 197, and 194 at 300 °C), respectively. In our study, based on the sheet tests to expose the ambient temperature variations in the oven, \(\alpha\) at RT and 300 °C is \(7.7 \times 10^5\) \(^{36}\) and \(7.3 \times 10^5\) S/m, respectively. The maximum magnetic flux density \(B_{\text{max}}\), fundamental frequency, modulation index, and switching dead time are set to 0.8 T, 50 Hz, 0.7, and 3.5 \(\mu\)s, respectively. Figure 2 shows the experimental DC hysteresis curves \((H_{\text{DC}}(B))\) without harmonics at each temperature (RT and HT). These experimental DC hysteresis curves\(^4,32\) at each temperature are used to build the play model. Five carrier frequencies \(f_c (1, 5, 10, 15,\) and 20 kHz) are tested.

### 3 Results and Discussion

Figure 3 shows experimental and numerical \(B - H\) hysteresis curves at RT and 300 °C of the AMM ring core, excited by the PWM inverter with a carrier frequency of 5 kHz. The calculated \(B - H\) curves are almost consistent with the experimental results. Here, the iron losses of the AMM ring fed by PWM inverter at \(f_c = 5\) kHz are about 0.33 W/kg at RT and 0.20 W/kg at 300 °C. The iron loss at 300 °C is smaller than that at RT.

Fig. 3(c) shows that the coercivity at RT is larger than that at 300 °C. As shown in Fig. 2, the coercivity of the DC hysteresis loops at HT becomes small because it is assumed that there appears thermal fluctuation (thermal energy) at HT. The coercivity also becomes small when the eddy current loss due to low conductivity at HT decreases for \(B - H\) hysteresis curves. In Fig. 2, the amorphous ring core at RT and HT exhibits the hysteresis loss at 0.8 T of about 4.6 and 2.6 mJ/kg, respectively. Therefore, it is considered that, owing to thermal fluctuation, the hysteresis losses decrease\(^37\) at HT\(^4\). As mentioned above, the electrical conductivity at 300 °C is smaller than that at RT. The classical eddy current loss is proportional to the electrical conductivity\(^4,38,39\). It is considered that the anomalous eddy current losses caused by magnetic domain wall movement decrease due to low conductivity at HT. Owing to the small electrical conductivity at HT, the eddy current loss decreases as temperature increases.

The torque of the motor depends on the current (magnetic field intensity) through the motor core. Figure 3(b) shows that the magnetic field intensity (current) at 300 °C is larger than that at RT at a few operating points for the same magnetic flux density. As shown in Fig. 2, the magnetic field intensity of DC hysteresis curves near \(B_{\text{max}}\) at HT is also larger than that at RT. It is considered that due to the thermal fluctuation the energy for aligning the magnetic moment near \(B_{\text{max}}\) increases with increasing tem-

### Fig. 2
Experimental DC hysteresis curves \((B_{\text{max}} = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9,\) and 1.0 T) used in our numerical simulations at each temperature: (a) RT and (b) 300 °C.
Fig. 3  $B-H$ hysteresis curves of AMM ring at RT and 300 °C fed by PWM inverter at $B_{\text{max}} = 0.8$ T and $f_c = 5$ kHz. Blue and red lines denote curves at RT and 300 °C, respectively. The enlarged view shows curves near maximum magnetic field intensity and minor loops of $B-H$ curves: (a), (b), and (c) shows experimental results, and (d), (e), and (f), the corresponding numerical results.

Fig. 4 Iron loss properties of AMM ring specimen with respect to carrier frequency at $B_{\text{max}} = 0.8$ T. Blue (red) points denote results at RT (300 °C). Carrier frequencies $f_c$ is set to 1, 5, 10, 15, and 20 kHz.

Fig. 5  Iron loss repartition between the hysteresis (red points, $W_{\text{hys}}$) and eddy current (blue points, $W_{\text{eddy}}$) losses under PWM inverter excitation at $B_{\text{max}} = 0.8$ T with Eq. (4): (a) RT. (b) 300 °C.

We can achieve highly accurate calculations for loss separation because fitting parameters and the experimental DC hysteresis curves are used in our numerical simulations. The average $W_{\text{eddy}}$ of the inverter-excited AMM rings at RT and at 300 °C accounts for 31% and 37% of the total iron losses, respectively. The ratio of $W_{\text{eddy}}$ to $W_{\text{ring}}$ at 300 °C is larger than that at RT. To realize low iron loss of HT and HS motor drive systems, it is important to reduce eddy current losses of the AMM cores at HT excited by inverter compared with the cases at RT. In addition, understanding the dynamic hysteresis properties also leads to simulating accurate motor loss characteristics. These results facilitate further research in loss reduction of HT and HS motor systems based on studies of magnetic properties under PWM inverter excitation.

4 Conclusion

Based on both experiments and numerical simulations, this study for the first time investigated iron loss and hysteretic properties of AMM ring core at RT and 300 °C under PWM inverter excitation. Owing to low electrical conductivity and thermal fluctuation at HT, the iron loss of AMM core fed by PWM inverter decreased as temperature increased similar like in the sinusoidal...
case. The torque of the motor with AMM became large at a few operating points under the same magnetic flux density. This was because the current (magnetic field intensity) at 300 °C was larger than that at RT at a few operating points. To realize low iron loss of HT and HS motor drive systems, it was important to reduce eddy current losses of AMM cores at HT excited by inverter compared with the cases at RT. These results facilitate further research regarding the loss reduction of HT and HS motor systems based on the iron loss and hysteretic properties of AMM core at HT under PWM inverter excitation. The future work will address further numerical and experimental studies under a wider range of magnetic flux density and temperatures to reveal general magnetic properties of AMM at HT under inverter excitation.

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