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Letter

Temperature Characteristics of the Dynamic Magnetic Loss of Ferrite

H. Saotome, K. Azuma and Y. Hamamoto

Faculty of Engineering, Chiba University, *1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan*

The dynamic magnetic loss in ferrites is obtained by subtracting the hysteresis loss, which is independent of the excitation frequency, from the iron loss. In the high frequency excitation region, the dynamic magnetic loss is the dominant component of the iron loss in ferrites. The iron loss in ferrite is temperature-dependent and this dependence has been described in product catalogs, where the hysteresis and dynamic losses are not separated. The catalog data are measured using sinusoidal wave voltage excitation, whereas ferrite cores are commonly used under rectangular wave voltage excitation in DC-DC converters. In this paper, the experimentally obtained temperature characteristics of the hysteresis and dynamic magnetic losses for rectangular wave voltage excitation are shown separately, and it is found that the two are different. This suggests that the physical mechanisms involved are different as well. Thus, it is important to consider the temperature characteristics of the dynamic magnetic loss to produce low-loss ferrites.

Key words: ferrite, Mn-Zn, iron loss, dynamic magnetic loss, *B-H* loop, temperature

1. Introduction

Ferrite cores are mainly used in DC-DC converters, where their switching frequencies are typically around 100 kHz. The eddy current loss in ferrites is negligible, even when they are excited at such high frequencies, because of the very high resistivity of grain boundaries. Thus, the power loss of ferrites is considered to be the magnetic loss. For a given magnetic induction maximum, B_m, the power loss of ferrites depends on the temperature. This dependence has been described in a product catalog, where the excitation voltage waveform used was sinusoidal [1)].

The magnetic loss in ferrites consists of hysteresis and dynamic magnetic losses [2)]. The area of the *B-H* loop varies with the exciting frequency, i.e., the time derivative of the magnetic induction, dB/dt. The hysteresis loss (J/m^3) is defined as the minimum *B-H* loop area with respect to the exciting frequency when B_m is kept constant, as shown by the broken line in Fig. 1. When the excitation frequency, or dB/dt, is increased, the *B-H* loop widens, as depicted by the solid line in Fig. 1. The dynamic magnetic loss (J/m^3) is defined by the gray area in the figure.

Although it is of great interest to investigate the generation mechanism of the magnetic losses, this is not easy. To determine whether the hysteresis and dynamic magnetic losses are generated by the same mechanism, the present authors measured the temperature behavior of both quantities in a previous study [3)]. We found no significant difference of the dynamic magnetic loss between at 0 °C and at room temperature. In that study [3)], we used TDK PC40 Mn-Zn ferrite, whereas here, we used TDK PC47, whose power loss temperature dependence is approximately 1.8 times stronger than that of PC40 [1)]. The dimensions of the core used in the experiments is shown in Fig. 2. The power loss measurements were carried out at 0 °C and 30 – 70 °C.

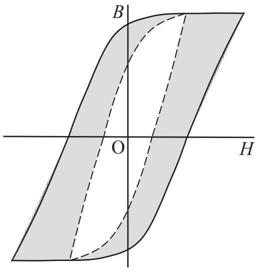


Fig. 1 *B-H* loop.

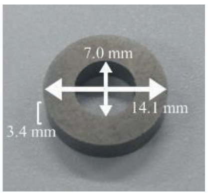
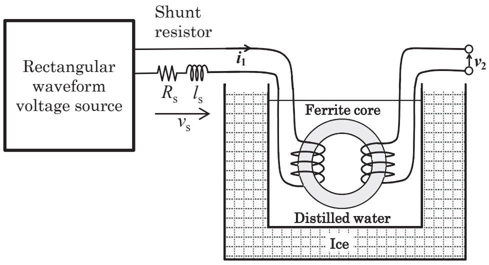


Fig. 2 Toroidal core used in experiments.

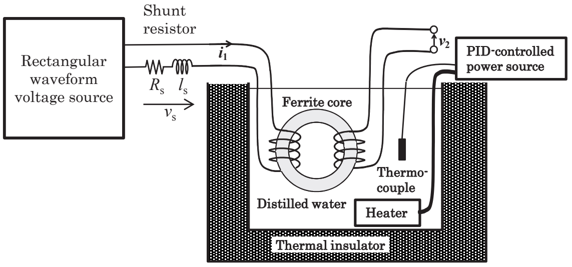
2. Instrumentation

In order to set the temperature of the ferrite core to 0 °C and 30 – 70 °C, the temperature control setups shown in Figs. 3(a) and 3(b), respectively, were prepared. The core was completely submerged in distilled water in both cases. In Figs. 3(a) and 3(b), the distilled water was surrounded by ice and a thermal insulator, respectively. In Fig. 3(b), the water temperature was controlled with a power source, heater, and thermocouple. The duration of the excitation was short enough to keep the rise in core temperature below 1 °C.

The product catalog for PC47 shows the temperature characteristics of the core loss under sinusoidal waveform voltage excitation at 100 kHz and B_m = 200 (mT). The measurement results obtained in the range of 30 °C to 70 °C using the present setup coincide with the



(a) At roughly 0 °C



(b) Above 30 °C

Fig. 3 Measurement setups.

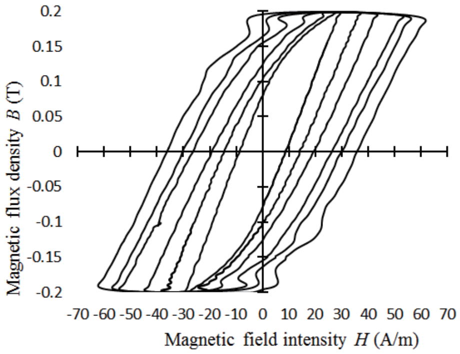
catalog data under the same conditions.

In this study, the ferrite core was excited by a rectangular waveform voltage, i.e., at constant $\mathrm{d}B/\mathrm{d}t$, because we wanted to measure the power loss of the ferrite with respect to the parameter $\mathrm{d}B/\mathrm{d}t$. The rectangular waveform voltage sources shown in Figs. 3(a) and 3(b) consisted of a function generator and an amplifier, or an FET inverter. The amplifier and FET inverter were used to generate $\mathrm{d}B/\mathrm{d}t$ smaller and larger than 200 mT/μs, respectively.

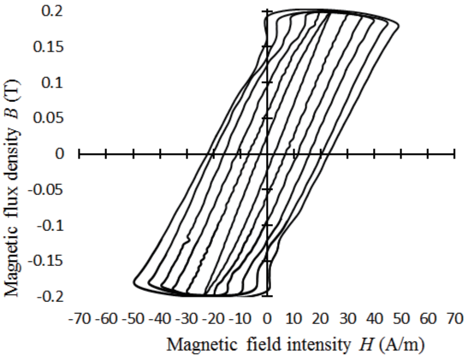
To measure the excitation current, i_1, a shunt resistor with a known stray inductance was used. The i_1 waveform was calculated by using the shunt resistor voltage, v_s, and the compensation for the deviation due to the stray inductance. *B-H* loops are obtained with i_1, the time integral of the search-coil-induced voltage, v_2, and the core dimensions. When the excitation current is too large, v_2 deviates from the rectangular waveform due to v_s. In such cases, the output waveform of the function generator is adjusted to compensate for the distortion [3)].

3. Measurement results

Six *B-H* loops measured at 0 °C and 70 °C are shown in Figs. 4(a) and 4(b), respectively. They were obtained under rectangular waveform voltage excitation with $\mathrm{d}B/\mathrm{d}t$ = 1, 200, 400, 600, 800 and 1000 mT/μs. The smallest and largest *B-H* loops in the figures correspond to 1 and 1000 mT/μs, respectively. The maximum magnetic flux density, B_m, was kept at 200 mT for each *B-H* loop. Between 0 °C and 70 °C, the power loss of the ferrite decreases with increasing temperature. The hysteresis loss corresponding to the area of the smallest *B-H* loop in each figure also decreases. Moreover, the

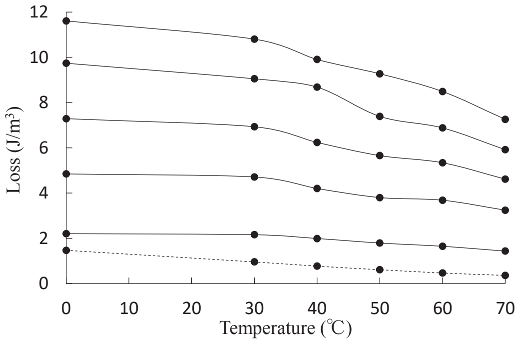


(a) 0 °C

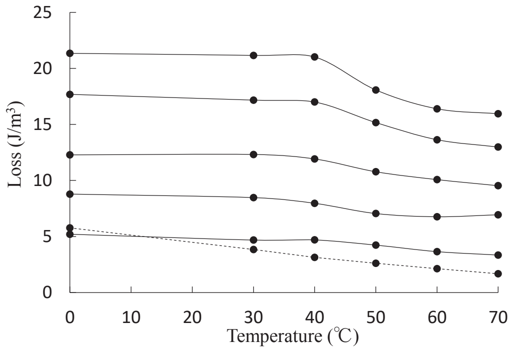


(b) 70 °C

Fig. 4 *B-H* loops (B_m = 200 mT).

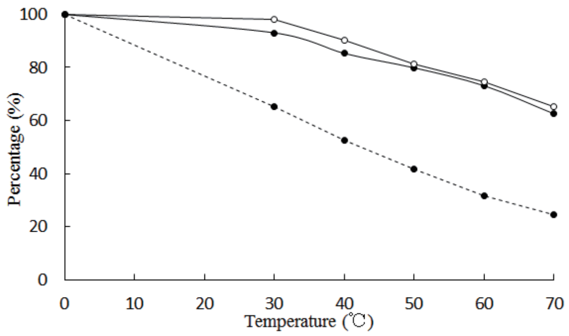


(a) B_m = 100 mT

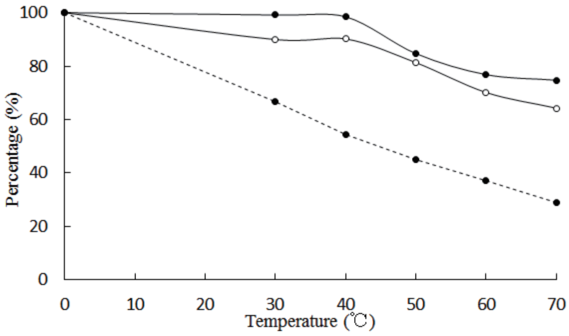


(b) B_m = 200 mT

Fig. 5 Temperature characteristics of the dynamic magnetic loss with $\mathrm{d}B/\mathrm{d}t$ = 1000, 800, 600, 400 and 200 mT/μs from the top down, respectively. The bottom broken lines show the hysteresis losses.



(a) B_m = 100 mT



(b) B_m = 200 mT

Fig. 6 Temperature characteristics of the dynamic magnetic loss: normalized values with respect to the values at 0 °C for dB/dt = 1000 (●) and 200 (○) mT/μs. The bottom broken lines show the hysteresis losses normalized to the values at 0 °C.

dynamic magnetic loss decreases slightly. In Fig. 4, the magnetic field intensities fluctuate a little near $\pm B_m$, i.e., the exciting current oscillates slightly when the rectangular waveform voltage changes its polarity very quickly. The fluctuation is caused by the stray capacitance of the winding. However, it does not influence the *B*-*H* loop areas, because the energy stored in the stray capacitance does not affect the area in a period. The capacitance energy is restored to the voltage source.

Similar to the experiments resulting in Fig. 4, *B*-*H* loops were also measured at 30, 40, 50, 60 and 70 °C. The temperature characteristics of the hysteresis and dynamic magnetic losses are shown in Figs. 5(a) and 5(b), where B_m is kept at 100 mT and 200 mT, respectively. The measured dynamic magnetic losses are plotted with dB/dt = 1000, 800, 600, 400 and 200 mT/μs from the top down, respectively, and the bottommost broken lines represent the hysteresis losses. The dynamic magnetic loss becomes larger than the hysteresis loss and dominates with increasing dB/dt, regardless of the temperature. To investigate whether the difference in temperature characteristics between the hysteresis and dynamic magnetic losses can be clarified, the normalized values were re-plotted (see Fig. 6), with 100 % representing the values at 0 °C for each of the losses. Figures 6(a) and 6(b) revealed that between 0 °C and 30 °C, the hysteresis loss decreased with temperature more steeply than the dynamic magnetic loss; the normalized hysteresis loss curves in Figs. 6(a) and 6(b) almost coincide. Thus, the temperature characteristics of the hysteresis and dynamic magnetic losses are different, which suggests that, microscopically, their generation mechanisms are not precisely the same.

4. Conclusions

The hypothesis that the dynamic magnetic loss corresponds to the eddy current loss in ferrite grains has been disproved [4)]. Thus, the dynamic magnetic loss must be caused by a magnetic phenomenon explainable by electron spins, as in the case of the hysteresis loss, whereas the eddy current can be explained by free electron motion. However, the experimental results presented here suggest that the generation mechanism of the dynamic magnetic loss cannot be exactly the same as that of the hysteresis loss, given the difference in their temperature characteristics.

The hysteresis losses, normalized to the values at 0 °C, decrease with temperature to a greater extent than the normalized dynamic losses. On the other hand, the temperature dependence of the dynamic magnetic loss in the raw data is stronger than that of the hysteresis loss. The dynamic magnetic loss is more dominant under large dB/dt conditions. Thus, ferrite manufacturers need to observe closely the temperature characteristics of the dynamic magnetic loss, rather than evaluating only the total magnetic loss.

References

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