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## Relationship between Residual Loss and Microstructure of Mn-Zn Ferrites

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**Abstract.** The core loss characteristics of the Mn-Zn ferrite cores with various grain sizes, electric conductivities and cross sectional areas are analyzed. A part of the residual loss depends on the grain size. It is 4 orders of magnitude larger than the intragrain eddy current loss estimated classically. On the other hand, the core loss calculated by using the dynamic magnetic loss parameter recently introduced by Saotome and Sakaki includes the part. This indicates that the part of the residual loss is related to the interaction between the applied field and the induced magnetic flux.

### 1. INTRODUCTION

The magnetic core loss of Mn-Zn ferrites has so far been analyzed by various methods. The core loss of a Mn-Zn ferrite core,  $P_c$ , consists of the hysteresis loss  $P_h$ , the eddy current loss  $P_e$  and the residual loss  $P_r$ . They are conventionally written as the following equation (1),

$$P_c = P_h + P_e + P_r = W_h \cdot f + \alpha \cdot A \sigma \cdot f^2 B_m^2 + P_r \quad \dots \quad (1)$$

where  $f$ ,  $B_m$ ,  $W_h$ ,  $A$  and  $\sigma$  are the exciting frequency, the maximum flux density, the hysteresis loss per one cycle, the cross sectional area of the core and the conductivity respectively.  $\alpha$  is a coefficient which depends on the geometry of the material specimen [1].

However, the details and the origins of the residual loss have not been made clear yet. In this study, we report the new results of the analyses of the relationship between the residual loss and the microstructure of Mn-Zn ferrites.

### 2. EXPERIMENTAL

The Mn-Zn ferrite cores with various grain sizes ( $d$ ), electric conductivities ( $\sigma$ ) and cross sectional areas ( $A$ ) were prepared. The grain size was varied by changing the sintering time, and the conductivity was changed by increasing the amount of addition of  $\text{SiO}_2$ , which is one of the additives. Their characteristics of the specimens are shown in table 1. The core losses of the toroidal cores were measured at the various exciting frequencies ( $f=1\text{kHz}\sim 1\text{MHz}$ ) and magnetic flux densities ( $B_m=25\sim 200\text{mT}$ ). The DC conductivity ( $\sigma$ ), the equivalent conductivity ( $g$ ) and the dielectric constant ( $\epsilon_r$ ) were determined by the frequency dependence of the impedance of the ferrite bar, which was measured with an impedance analyzer. The equivalent conductivity is used for the dielectric loss estimation. The permeability  $\mu_r$  was also measured by using the impedance analyzer. The microstructures were examined by optical micrograph. All characteristics were measured at room temperature.

Table 1. The materials and their characteristics

Specimen No.	A (mm <sup>2</sup> )	d (μm)	σ (S/m)	g (S/m)	μ <sub>r</sub>	ε <sub>r</sub>	λ <sub>h0</sub> (Ω/m)		λ <sub>f</sub> (Ω/m)
							at 25mT	at 200mT	
A	1	25.7	0.12	44	2920	90000	570	310	45000
	2	51.2							
	3	102.5							
B	1	37.9	15	54	3510	120000	500	340	41000
	2	37.9	17	55	3530	120000	530	360	34000
	3	38.4	19	60	3510	120000	510	380	28000
C	1	37.9	12	52	3390	80000	520	270	36000
	2	37.8	12	51	3370	100000	520	300	44000
	3	37.7	12	46	3050	100000	540	290	47000

3. RESULTS AND DISCUSSION

3.1 Conventional Method

The eddy current loss, calculated with the equation (1), was less than 2% of the core loss except for the specimen C-1.  $P_e$  [W/m<sup>3</sup>], obtained by subtracting the measured  $P_h$  and the calculated  $P_c$  from  $P_c$ , increased in proportion to the square of the product of  $f$  [Hz] and  $Bm$ [T]. Moreover the factor  $a$  [S·m] depended on the grain size  $d$  [m] and the equivalent conductivity  $g$ [S/m], but did not depend on the other parameters. The equivalent conductivity corresponds with the conductivity of the grain, therefore the intragrain eddy current loss  $P_{eg}$  is given as  $\beta d^2 g f^2 B m^2$ . The residual loss could be fitted by the following formula,

$$P_r = P_{eg} + P'_r = a \cdot f^2 B m^2 = [(1.4 \pm 0.1) \cdot 10^4 d^2 g + (4.8 \pm 0.1) \cdot 10^{-4}] \cdot f^2 B m^2 \quad \dots (2)$$

However,  $P_{eg}$  is 4 orders of magnitude larger than the intragrain eddy current loss calculated by the classical formula[1]. It is too large to be explained by the intragrain eddy current or the intergrain eddy current through several grains with the defective boundaries. Therefore, it was attempted to analyze the core losses with a new model in order to find out the origin of this loss.

3.2 Analyses Of Core Losses By New Model

Saotome and Sakaki[2,3] have recently introduced a new parameter which represents the dynamic behavior of the residual loss, and the parameter is named "dynamic magnetic loss parameter,  $\lambda_f$ ". According to this model, the magnetic field  $H$  and the electric field  $E$  are given as the equations (3) and (4), and the core loss is calculated by using the equation (5),

$$H = \frac{1}{\mu_0 \mu_r} B + j \frac{\omega_0}{\lambda_{h0}} B + j \frac{\omega}{\lambda_f} B \quad \dots (3), \quad E = \frac{1}{\epsilon_0 \epsilon_r} D + j \frac{\omega}{g} D \quad \dots (4)$$

$$P_c = P_e + P_d + P_m = \int_V \sigma E(r)^2 dv + \int_V \frac{1}{2} [E(r)\{j\omega D(r)\} + \overline{E(r)}\{j\omega D(r)\}] dv + \int_V \frac{1}{2} [H(r)\{j\omega B(r)\} + \overline{H(r)}\{j\omega B(r)\}] dv \quad \dots (5)$$

where  $B$  is the flux density,  $D$  is the electric displacement,  $\mu_0$  and  $\epsilon_0$  are the permeability and permittivity of vacuum,  $\lambda_{h0}$  is the hysteresis parameter which is estimated from the core loss measured at  $\omega_0$  (=1kHz),  $\omega$  is the exciting circular frequency, and  $j$  is the imaginary unit.  $P_d$  is the dielectric loss, which is the ohmic loss by the displacement current.  $P_m$  is the magnetic loss including the hysteresis loss.

Our results almost agreed with this model in a wide range of flux densities up to 200mT as shown in figure 1. It shows that this model is also applicable in the high induction range. The estimated  $P_m$  occupied more than 90% of  $P_c$  at even 1MHz.  $P_d$  increased in proportion of the fourth power of the exciting frequency, and it was much smaller than  $P_{eg}$  below 1MHz. The calculated  $\lambda_f$  depended on the grain size as shown in figure 2. These results indicate that the residual loss includes the one related to the magnetic domain structure depending on the grain size.

4. CONCLUSION

This paper has pointed out that a part of the residual loss depends on the grain size. It is much larger than the intragrain eddy current loss, and besides it is not produced by the induced electric field but by the direct interaction between the applied field and the induced magnetic flux.

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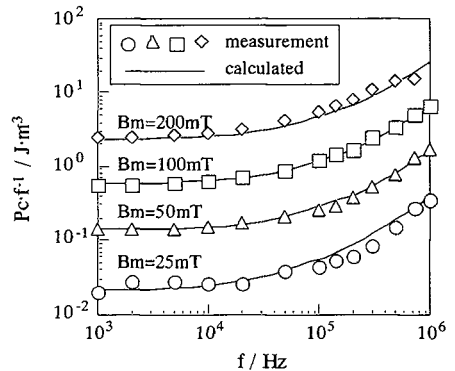


Fig. 1. The frequency dependence of the core loss of the specimen B-1.

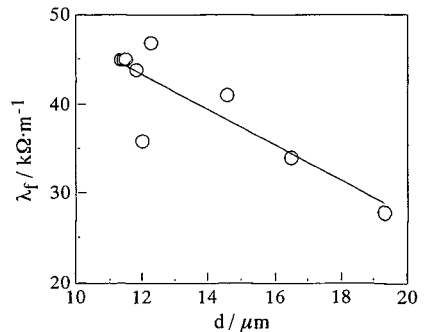


Fig. 2. The grain size dependence of the dynamic magnetic loss parameter  $\lambda_f$ .