**Relationship between Power Loss at High Frequency and the Microstructure of Mn-Zn Ferrites**

**T. KAWANO, A. FUJITA and S. GOTOH**

Technical Research Laboratories, Kawasaki Steel Corporation
Kawasakidori 1-1-chome, Mizushima, Kurashiki 712, Japan

Abstract - Frequency dependence of power loss of Mn-Zn ferrite was investigated in relation with the complex permeability in the frequency range 10 kHz - 5 MHz and the temperature range 23 - 120°C. The residual loss, Pr, occupies more than half of the total power loss at frequency above 1 MHz and exhibits a close relationship with the imaginary part of the permeability, \( \mu' \). Experimental frequency characteristics of \( \mu' \) can be explained by the dimensional resonance of the electromagnetic wave calculated by the Maxwell equations assuming the homogeneous ferrite body. We investigated the microstructure and the electromagnetic properties preferable for the power ferrite with low loss at high frequency.

I. INTRODUCTION

Mn-Zn ferrites have been widely used as transformers or noise filters in electric devices. They are used at increasingly higher driving frequency for miniaturization. The reduction of power loss, which increases drastically at frequency above 100 kHz, has been very important.

Many attempts have been made to analyze the effects in order to obtain low loss material. They focused on eddy current loss which increases in proportion to the frequency and the inverse of electrical resistivity. The resistivity is raised by introducing various additives such as SiO\(_2\), CaO, etc., which are distributed preferentially at the grain boundary. However the reduction of the resistivity at high frequency seems inevitable since the grain boundary layers act as capacitor, and then the reactance, \( 1/(2\pi fC) \), decreases at high frequency. On the other hand there are some reports [1][2] that insist on the important role of residual loss at high frequency. But it has not been clarified what is the origin of the residual loss and how to control it. Saotome et. al. proposed a new method[3] to describe quantitatively the frequency dependence of power loss using dynamic magnetic loss parameter, but its essential meaning on the ferrite has not been made clear yet.

Based on these studies, we analyzed the frequency dependence of power loss and permeability as a function of grain size and also of composition. We will also discuss about the origin of the residual loss on the point of the dimensional resonance of the electromagnetic wave which is calculated by the Maxwell equations.

II. EXPERIMENTAL

A. Sample Preparation and Characterization

Toroidal cores of Mn-Zn ferrite with various ZnO content were prepared by the conventional method. Each core was 19 mm in O.D., 10 mm in I.D. and 5 mm in thickness. Sintering temperature and amount of CaO were changed in order to control grain size. The characteristics of the samples are shown in Table 1.

Power loss \( P_c \) and absolute complex permeability \( \mu_a = (\mu' - j\mu") = Bm/Hm \) were measured with a B-H analyzer (Iwatsu, SY-8243) at frequency between 10 kHz and 5 MHz. The bar samples were cut from the toroidal cores to measure impedance spectra with a gain phase analyzer (Hewlett-Packard, 4194A). AC electrical resistivity was then calculated based on the R-C parallel circuit. All of these measurements were performed in the temperature range 23 - 120°C.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>ZnO (mol%)</th>
<th>CaO (wt%)</th>
<th>Ts (°C)</th>
<th>( \rho ) (Ωm)</th>
<th>d (μm)</th>
<th>( \mu'\mu'' )</th>
<th>( \mu_a )</th>
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<tbody>
<tr>
<td>A</td>
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<td>1330</td>
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<td>5270</td>
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<td>1920</td>
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<td>0.056</td>
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<td>1120</td>
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<td>1260</td>
<td>1740</td>
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<tr>
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</tr>
</tbody>
</table>

Ts : sintering temperature, \( \rho \) : specific resistivity, d : grain size, \( \mu_i \) : initial permeability at 1 kHz, 23°C, \( \mu_a \) : absolute permeability at 200 kHz, 50 mT, 90°C.

B. Analysis of Power Loss and Calculation of Permeability Spectra

Hysteresis loss, \( P_h \), was evaluated as the linear part of loss curve versus frequency. Eddy current loss, \( P_e \), was calculated through the classical theory based on the macroscopic eddy current within the cross section of the core. \( P_e \) is given by

\[
P_e = \left( \pi / 4 \right) f B_m^2 S / \rho ,
\]

(1)
where $B_m$ is the maximum magnetic flux density, $S$ is the cross sectional area of the toroidal core, and $\rho$ is the AC specific resistivity. Residual loss $P_r$ was evaluated as $P_c - P_h - P_e$.

The apparent complex permeability $\mu_{app}$ was calculated from the magnetic field inside the core, based on the Maxwell equations on the assumption that the core is homogeneous[4]. Then $\mu_{app}$ is expressed by

$$\mu_{app} = \mu(\mu, \rho, \varepsilon, f, r)\mu,$$

(2)

where $\mu$ is the constant DC permeability, $\rho$ is the resistivity, $\varepsilon$ is the permittivity, $f$ is the frequency, and $r$ is the equivalent cross sectional radius of the toroidal core.

We substituted the absolute permeability, $\mu_{a}$, for $\mu$. Conventional Mn-Zn ferrites have large real and imaginary parts of the relative permittivity in the order of $10^5 - 10^6$[3][4] which remarkably affect the frequency dependence of $\mu_{a}$.

III. RESULTS AND DISCUSSIONS

Sample A is a commercial ferrite material used in the frequency range up to 200 kHz. The frequency dependence of $P_c$, $P_h$, $P_e$, and $P_r$ is shown in Fig. 1. $P_r$ increases approximately in proportion to $f^{-2}$ and becomes dominant at frequency above 200 kHz. $P_h$ occupies the major part of $P_c$ at frequency below 100 kHz so that we have paid much attention to decrease $P_h$ which originates from the displacement of the magnetic domain wall. One of the novel methods to reduce $P_h$ is to increase grain size and choose the composition with low magnetocrystalline anisotropy and magnetostrict constant, which lead to the domain wall motion easier.

Contribution of $P_r$ is rather important when the ferrite is used at frequency above 500 kHz. Fig. 2 indicates the close relationship between $P_r$ and $\mu_a''$ of all the samples. $P_r$ increases with $\mu_a''$, independently of temperature.

Grain size and ZnO content were changed in order to control the frequency dependence of the complex permeability. Although sintering at lower temperature led to lower $\mu_a''$, non-spinel phase remained left (sample H) when sintered below 1100°C. Therefore some special method will be required to obtain low-loss ferrite. Decrease in ZnO content also led to lower $\mu_a'$ as shown in Fig. 3. As $\mu_a'$ decreases, the $\mu_a''$ peak is shifted to higher frequency, and consequently $P_r$ given by $\mu_a''$ at frequencies below its peak can be reduced not only by making grain size smaller but controlling the main composition of the ferrite. However, the important problem to be elucidated is the origin of the resonance or the relaxation.

The Rotational resonance as the Snoek’s limit[5] is known for Ni-Zn ferrites whose $\mu_a'$ are smaller than 1000. Based on this theory we can estimate the resonant frequency of the spin rotation, $f_r$, which is given by

$$f_r = \gamma I_s / (3\pi \mu_a \chi_i),$$

(3)

where $\gamma$ is the magnetomechanical ratio, $I_s$ is the saturated magnetization and $\chi_i$ is the relative magnetic susceptibility. When $I_s$ of 0.5 T and $\chi_i$ of 1700 are introduced into equation (3), $f_r$ is evaluated at 5.6 MHz. In addition, the frequency of the magnetic domain wall resonance is estimated at above 10 MHz[6]. These values are higher than the measured one as shown in Fig. 4.
think that the permeability spectra of Mn-Zn ferrite cores are determined by the dimensional resonance occurred in the individual cores[3]. Assuming that the core size, resistivity, permeability, and frequency are constant, suppressing $\varepsilon$ would be the most desirable way to reduce $\mu''$ shown as $\mu_q''$ in Fig. 4.

IV. CONCLUSIONS

Decrease in grain size and molar ratio of ZnO resulted in decrease in $\mu_a'$ along with increase in hysteresis loss and decrease in residual loss. Then the ideal microstructure of Mn-Zn ferrites with the lowest power loss for the applied frequency is determined considering that each of these loss factors exhibits different frequency dependence. In particular, the residual loss occupies more than half of the total loss at frequency above 1 MHz and is closely associated with $\mu_a''$. The frequency characteristics of $\mu_{app}$ calculated with the Maxwell equations well explain the experimental result, so that we think the increase in $\mu_a''$ is caused by the dimensional resonance which occurs depending on both the sample dimension and the macroscopic electromagnetic properties of the core. The calculation shows that $\varepsilon$ remarkably affects the frequency dependence of $\mu_a''$, therefore reducing $\varepsilon$ would be the most expectative way to suppress $P_r$ without raising $P_h$ and $P_e$.

REFERENCES