Analysis of eddy current loss and magnetization process in Mn–Zn ferrites for power supplies

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Magnetization process in Mn–Zn ferrites has been investigated by analyzing eddy current loss obtained from the relationship between power loss and electrical resistivity. The eddy current loss caused by domain wall displacement was obtained by subtracting the estimated eddy current loss of uniform magnetization rotation from the experimental eddy current loss. The contribution of the domain wall displacement to the eddy current loss is about 30% at 100kHz and decreases as increasing frequency, followed by vanishing in the frequency range above 600kHz. This result shows that as increasing frequency the magnetic domain is subdivided into smaller size and the uniform magnetization dominates the magnetization process in the high frequency range.

Key words: Mn–Zn ferrite, power loss, eddy current loss, magnetization rotation, domain wall displacement

1. Introduction

Mn–Zn ferrites are widely used as transformer cores in switching power supplies which are required to be miniaturized. The miniaturization of the switching power supplies requires Mn–Zn ferrites to have low power loss at high frequency and at large induction. The power loss, \( P_L \), has been considered to consist of hysteresis loss, \( P_h \), eddy current loss, \( P_e \), and residual loss, \( P_r \). In previous papers \(^{27, 33}\), we showed that the eddy current loss and the residual loss can be obtained separately from the relationship between the power loss and electrical resistivity at a temperature, \( T_{\text{in}} \), at which initial permeability shows a secondary maximum. This analysis showed that more than half of the power loss is attributed to the residual loss, of which reduction is effective developing low loss materials. Therefore it is necessary for the reduction of the residual loss to understand the mechanism of the causing the residual loss. In previous paper \(^{47}\), the domain size was obtained by applying the bar-like domain wall model \(^{5}\) to the experimental eddy current loss and the origin of the residual loss was concluded to be the spin resonance inside the domain wall accompanied by the high-speed domain wall displacement. The eddy current loss, however, cannot be described only by domain wall displacement because the magnetization rotation contributes to the magnetization process \(^{6}\) as well.

The purpose of this paper is to obtain the contribution of both the magnetization rotation and the domain wall displacement to the magnetization process in power ferrites.

2. Experimental Procedures

Mn–Zn ferrite samples with the chemical composition of \( \text{Mn}_{0.74}\text{Zn}_{0.18}\text{Fe}_{2.06}\text{O}_4 \) were prepared by conventional powder metallurgical process. The samples with different electrical resistivity were prepared by means of changing the amount of additives, \( \text{SiO}_2 \) and \( \text{CaO} \), as listed in Table 1. The measurements and analyses of the power loss and electrical resistivity were described in the previous paper \(^{7}\).

<table>
<thead>
<tr>
<th>#</th>
<th>( \text{SiO}_2 ) (wt%)</th>
<th>( \text{CaO} ) (wt%)</th>
<th>dc resistivity at R.T. (( \Omega \text{ m} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.014</td>
<td>0.008</td>
<td>0.017</td>
</tr>
<tr>
<td>2</td>
<td>0.023</td>
<td>0.008</td>
<td>0.087</td>
</tr>
<tr>
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</tr>
<tr>
<td>4</td>
<td>0.025</td>
<td>0.040</td>
<td>0.67</td>
</tr>
<tr>
<td>5</td>
<td>0.033</td>
<td>0.042</td>
<td>3.84</td>
</tr>
</tbody>
</table>

3. Results and Discussion

3.1. Computation of the eddy current loss

As shown in previous paper \(^{27}\), the dependency of \( (P_L - P_h) \) on the electrical resistivity, \( \rho \), at \( T_{\text{in}} \) follows the Eq. (1).

\[
P_B - P_h = k(fB_m) / \rho + C(fB_m),
\]

where, \( P_B \) is the power loss, \( P_h \) the hysteresis loss, \( f \) frequency, \( B_m \) magnetic flux density, \( k \) and \( C \) constant depending on the frequency and the magnetic flux density respectively.

In order to obtain \( k \), the power losses of the samples listed in Table 1 were measured at frequencies between 100kHz and 1MHz for magnetic flux densities between 10mT and 100mT. The electrical resistivities were also measured by AC current. \( T_{\text{in}} \) of all these samples are all 100 \( ^\circ \text{C} \). Fig.1 shows the plot of \( (P_B - P_h) \) versus \( 1/\rho \) at
Fig. 1 Relationship between \((P_e - P_h)\) and \(1/\rho\) at \(T_{\text{ms}}\).

\(B_m=50\text{mT}\). As seen in Fig. 1, \((P_e - P_h)\) is proportional to \(1/\rho\) for the whole frequencies and magnetic flux densities. The dependencies of \(k\) on both the frequency and the magnetic flux density are shown in Fig. 2. From Fig. 2, \(k\) is obviously proportional to both \(f^2\) and \(B_m^2\). Therefore, \(k/\rho\) is identified as the eddy current loss, \(P_e\), shown in Eq. (2).

\[
P_e = k/\rho. \tag{2}
\]

The eddy current loss from \(k\) for sample #5 are shown by solid lines, in Fig. 3. In this figure, the curves shift upwards from the \(f^2\)-relationship above 500kHz because of decreasing in the AC electrical resistivity as increasing frequency.

3.2. Eddy current loss caused by the domain wall displacement

Both the magnetization rotation and the domain wall displacement contribute to the magnetization process\(^6\). As the samples examined here contain additives as listed in Table 1, the electrical resistivity of the samples is thought to be dominated by the electrical resistivity of the grain boundary. Then the eddy current loss given by Eq. (2) is caused by the eddy current which circulates in the cross section of the sample through the grain boundary. Therefore, the eddy current loss shown in Fig. 1 includes the eddy current loss caused by the uniform magnetization rotation, denoted by \(P_{\text{rot}}\). \(P_{\text{rot}}\) is given by Eq. (3):\(^6\)

\[
P_{\text{rot}} = \frac{\pi R^2}{4} \cdot \frac{f^2 B_m^2}{\rho}, \quad \text{W/m}^3, \tag{3}
\]

where \(R\) is the equivalent radius given in meter corresponding to the cross-sectional area, \(f\) given in Hz, \(B_m\) given in tesla, \(\rho\) given in \(\Omega\) m. The remainders subtracted \(P_{\text{rot}}\) from \(P_e\) given by Eq. (2) are the eddy current loss caused by the domain wall displacement, denoted by \(P_{\text{wall}}\) as seen in Eq. (4).

\[
P_{\text{wall}} = P_e - P_{\text{rot}} \tag{4}
\]

In Fig. 3, the calculated eddy current loss caused by the uniform magnetization rotation for sample #5 are shown with broken lines. From Fig. 3, the difference

Fig. 2 Dependencies of the gradient \(k\) on the frequency and the magnetic flux density.

Fig. 3 Frequency dependencies of the experimental eddy current loss and the calculated one in which the solid lines show the experimental values and the broken lines show the calculated ones.

Fig. 4 Frequency dependence of the eddy current loss caused by the domain wall displacement.

Fig. 5 Frequency dependence of the ratio of the eddy current loss caused by the domain wall displacement to the experimental eddy current loss.

between the experimental eddy current loss and $P_{ew}$ decreases as increasing frequency and diminishes at above 600kHz.

The eddy current loss caused by the domain wall displacement was calculated by Eq.(4) and was shown as a function of the frequency in Fig.4. From Fig.4, $P_{ew}$ take maximums at the frequency range between 300kHz and 500kHz and decrease as increasing frequency followed by disappearing at the high frequency range.

In Fig.5, the ratios of $P_{ew}$ to $P_e$ are shown as a function of the frequency. The ratios occupy 25% ~ 30% of $P_e$ at 100kHz and decrease gradually as increasing frequency. From these tendencies, it seems that domain wall cannot move at the frequency range above about 600kHz. The ferrite cores, however, do not lose the non–linear characteristics of the magnetization curves even at the high frequency range above 600kHz. These non–linear characteristics of the magnetization curves may well indicate the contribution of the domain wall displacement to the magnetization process. Therefore, the non–linear characteristics of the magnetization curves and the disappearance of the contribution of the domain wall displacement to the eddy current loss means that the magnetic domains are subdivided into smaller size and the uniform magnetization process becomes predominant at the high frequency range.

4. Conclusions

The power loss of Mn-Zn ferrites for switching power supplies was investigated with comparing the experimental eddy current loss and the calculated one by the uniform magnetization rotation. The following results were obtained.
(1) The eddy current loss obtained experimentally coincides with the calculated eddy current loss by the uniform magnetization rotation at the high frequency range above 600kHz.
(2) The contribution of the domain wall displacement to the eddy current is less than 30% and disappears above 600kHz.
(3) It is thought that the magnetic domains are subdivided at the high frequency range.

References