Generation of extra eddy current loss in Mn-Zn ferrites in the high frequency range

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In this work, AC conductivity, complex impedance and power loss (P_{cv}) in the Ta_2O_5 doped Mn-Zn ferrites have been comprehensively investigated. In the high frequency range, AC conductivity increases remarkably with increasing frequency. It is found that the traditional loss separation method underestimates eddy current loss (P_{ev}) and overestimates residual loss (P_{rv}) due to no consideration of the frequency influence on conductivity. Based on the analysis of AC conductivity, the P_{ev} generation mechanism in the high frequency range has been clarified and the loss separation method has been modified. The Ta_2O_5 addition effectively reduces all three parts of loss including hysteresis loss (P_{hv}), P_{ev} and P_{rv}, and the Mn-Zn ferrite with low P_{cv} in the frequency range of 1-3 MHz is developed. The optimal sample shows P_{cv} as low as 15, 65 and 359 kW/m^3 at 1MHz/30mT, 2MHz/30mT and 3MHz/30mT at 30 °C, respectively.

Keywords: Soft magnetic materials, Mn-Zn ferrites, AC conductivity, eddy current loss

1. Introduction

Soft magnetic Mn-Zn ferrites have been extensively used as core materials in power electronic devices. With the development of electric vehicles and 5G communication technology, power electronic devices are accelerating towards miniaturization and high frequency. However, power loss (P_{cv}) of traditional Mn-Zn ferrites increases dramatically when frequency (f) increases at MHz frequencies, which hinders the application of Mn-Zn ferrite in the wide band gap (WBG) semiconductor based high-frequency electronic devices. Generation mechanism of P_{cv} is the key issue for developing the low-P_{cv} Mn-Zn ferrite. Generally, P_{cv} consists of hysteresis loss (P_{hv}), eddy current loss (P_{ev}) and residual loss (P_{rv}) based on different generation mechanisms and is expressed as the equation (1):

$$P_{\mathrm{cv}} = P_{\mathrm{hv}} + P_{\mathrm{ev}} + P_{\mathrm{rv}} = K_{\mathrm{H}} B_{\mathrm{m}}^3 f + K_{\mathrm{E}} D^2 B_{\mathrm{m}}^2 \sigma f^2 + P_{\mathrm{rv}} \quad (1)$$

In the traditional model of loss separation, σ is simplified as DC conductivity (σ_{DC}) independent of frequency. However, the conductivity of Mn-Zn ferrite will change with frequency. The variation of resistivity will lead to the change of P_{ev} and consequently P_{cv}. Thus, the traditional loss separation method is inapplicable for analyzing the loss generation mechanism at high frequencies, especially MHz frequencies. In this work, AC conductivity, complex impedance and high-frequency P_{cv} in the Ta_2O_5 doped Mn-Zn ferrites have been comprehensively investigated.

2. Results and discussion

The influence of Ta_2O_5 on P_{cv} was investigated. With increasing Ta_2O_5 content, P_{cv} decreases firstly and then increases. P_{cv} of the optimal sample, at 30 °C is as low as 15, 65 and 359 kW/m^3 at 1MHz/30mT, 2MHz/30mT and 3MHz/30mT, respectively. The addition of an appropriate amount of Ta_2O_5 improves the performance of high frequency power loss effectively.

For all samples with Ta_2O_5 addition, conductivity σ increases very slowly in the low-frequency range (ω below 500 kHz). When ω increases above 500 kHz, σ increases remarkably. σ obeys the following equation: $\sigma_{\mathrm{AC}} = \sigma_{\mathrm{DC}} + \sigma_\omega = \sigma_{\mathrm{DC}} + \mathrm{A}\omega^s$, where σ_{DC} is DC conductivity and s is a parameter reflecting the change speed of conductivity with frequency. The relationship between P_{cv}/f and f for the Mn-Zn ferrites with different Ta_2O_5 content has been further invesitigated, shown in Fig. 1. In the traditional loss separation method according to equation (1), σ is supposed to be frequency-independent, which is basically correct in the low frequency range. However, when frequency increases to the MHz region, σ_{AC} increases remarkably. Therefore, the traditional loss separation method is not applicable. σ_{AC} has been used to replace σ and equation (1) is modified as the following:

$$\frac{P_{\mathrm{cv}}}{f} = \frac{P_{\mathrm{hv}}}{f} + \frac{P_{\mathrm{ev}}}{f} + \frac{P_{\mathrm{rv}}}{f} = K_{\mathrm{H}} B_{\mathrm{m}}^3 + K_{\mathrm{E}} D^2 B_{\mathrm{m}}^2 \sigma_{\mathrm{AC}}(f) f + \frac{P_{\mathrm{rv}}}{f} \quad (2)$$

P_{ev} without conductivity correction is represented by P_{ev0} and the additional P_{ev} related with frequency is represented by extra eddy current loss ($P_{ev\text{-}extra}$). The σ_{AC} data have been employed to re-estimate eddy current loss. $P_{ev\text{-}extra}$ is estimated by employing the σ_{AC} data and shown in blue in Fig. 1. Obviously, P_{ev} exceeds the traditional P_{ev0}, and P_{ev} is composed of P_{ev0} and $P_{ev\text{-}extra}$. There, P_{rv} derived from the rest of P_{cv} is overestimated in the traditional model. $P_{ev\text{-}extra}$ accounts for 43% of the total eddy current loss P_{ev}, indicating that the loss originating from the variation of σ_{AC} is remarkable in the high frequency range. An appropriate addition of Ta_2O_5 (up to 600 ppm) reduces all P_{hv}, P_{ev} and P_{rv}.

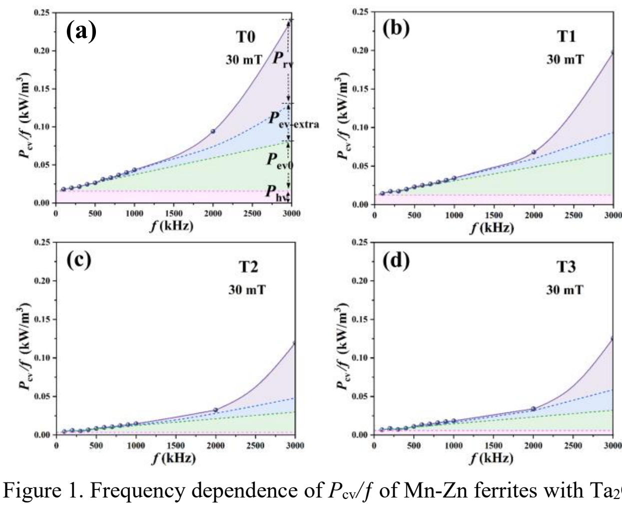

Figure 1. Frequency dependence of P_{cv}/f of Mn-Zn ferrites with Ta_2O_5 addition: (a) 0, (b) 300, (c) 600 and (d) 900 ppm.