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Grain Size Dependency of the Steinmetz Coefficient of Soft Ferrite Power Losses

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Abstract. A comparison was made between the power loss behaviour of MnZn ferrites having average grain sizes ranging from 4 to 16 μm . In the finer grains, the power loss at induction levels above 50 mT was observed to rise anomalously, as did the Steinmetz coefficient y . An explanation is given involving irreversible rotational loss in monodomain grains.

1. INTRODUCTION AND EXPERIMENTAL RESULTS

Low-loss power ferrites for high frequency applications possess in general small grains, this to suppress the high frequency domain wall damping losses and the eddy current losses (cf. [1] and [2]). Although at frequencies above 500kHz usually the induction level B is kept at typically 50 mT, further miniaturisation requires higher power density, so higher induction. In this paper we investigated, in how far the finer grained ferrites are suitable for such high-frequency/ high-induction usage.

To this end we compared the power losses of MnZn ferrites having equal compositions, equal impurities and having average grain sizes of 4, 8 and 16 μm , respectively. Up to 50 mT we observed a normal loss behaviour. When going to larger induction levels of 100 mT and more, however, the smaller grains clearly exhibited a steeper rise in power loss (see slopes in Figure 1). Figure 2 gives these slopes as the Steinmetz coefficients y , since Power Loss = constant $\times F^x \times B^y$. A pronounced rise of y is seen for small grains near 100 $^\circ$ C. Below we list the various values of y obtained at 100 $^\circ$ C.

at 100 kHz: $y = 3.25, 3.15$ and 2.80 , respectively for the average grain sizes $D = 4, 8, 16 \mu\text{m}$;

at 500 kHz: $y = 3.25, 2.50$ and 2.20 , respectively for the average grain sizes $D = 4, 8, 16 \mu\text{m}$.

Figure 1: Power losses, experimental and theory (eq.(5))

Figure 2: Steinmetz coefficient, effects of grain size and temperature.

2. THEORETICAL MODEL

Since the Steinmetz coefficients y exceed the value of two, we are dealing with *non-linear* magnetization processes and, above 500 kHz, in fact more with *rotational magnetization* of M in domains than with domain wall movements (cf.[1]).

Moreover, ref.[2] demonstrated that in small MnZn ferrite grains the domain walls are reduced in number, while they even disappear below a grain size of $3\mu\text{m}$ as the grain becomes *monodomain*. Therefore, we ascribe the anomalous increase of y for finer grains to *irreversible rotational loss inside monodomains*. As the finer grained ferrites will contain a considerable portion of monodomain grains smaller than $3\mu\text{m}$, for a large induction B their magnetic moments M inside those grains will suddenly sweep irreversibly from their original easy axes to a next easy axis. This causes extra power loss at larger B in fine grains. It would explain as well the maximum y near 100°C in Fig.2: the critical grain size for monodomains depends on anisotropy K as $\sqrt{1/K(T)}$ (cf. [2]), so near 100°C more grains acquire a monodomain state.

To further quantify our model we calculate the conditions for irreversible rotation of M . Consider a particular grain having an easy axis lying at an angle θ_0 with respect to the (fixed) direction of an applied magnetic field H ; after rotation of M over an angle θ , an angle $\theta - \theta_0$ results between M and H . The rotation of M is a result of the torques exerted by the crystal anisotropy energy E_{AN} and by the magnetostatic energy E_H between M and H :

$$(1) \quad E_{AN} = K \cdot \sum_{i,j} \cos^2 \alpha_i \cos^2 \alpha_j \quad \text{and} \quad (2) \quad E_H = -\mu_0 M_s H \cos(\theta - \theta_0),$$

wherein α_i are the angles between M and the three crystal axes $\langle 1,0,0 \rangle$ and $M_s = |M|$ is the magnitude of the saturation magnetization. Assume K to be negative and suppose easy axis #1 along $(1,1,1)$ and the next easy axis #2 along $(-1,1,1)$. The maximum anisotropy energy to overcome if M rotates from $(1,1,1)$ to $(-1,1,1)$ is $-K/12$, this in the direction $(0,1,1)$. Next, we obtain for the *maximum anisotropy torque* in the middle of $(1,1,1)$ and $(0,1,1)$, at about $\theta_m = (0.30, 0.67, 0.67)$, a value of $\delta E_{AN}/\delta\theta = 0.21 K$. For rotation to be irreversible, the torque $\delta E_H/\delta\theta$ exerted by H on M must exceed that value:

$$(3) \quad \delta E_H/\delta\theta \text{ at } \theta_m \sim 18^\circ \text{ is equal to } \mu_0 M_s H \sin(\theta_0 - \theta_m) \geq 0.21|K| \quad (\text{irreversibility condition})$$

Next we randomize θ_0 over all grain orientations to collect all irreversibly rotating monodomains, giving $(\cos\theta_1 - \cos\theta_2)/2$, where $\theta_{1,2}$ are the values of θ_0 for the “=” condition in eq.(3). Rewriting eq.(3) by introducing for the monodomain grain an approximate expression for its reversible rotational permeability, $\mu_R = \mu_0 \times M_s^2 / 2|K|$, and by defining the maximum induction in the grain as $B_{MAX} = \mu_0 \mu_R H$, we can approach $\sin(\theta_{1,2} - \theta_m)$ by the expression $\mu_0 M_s / 9.5 B_{MAX}$, resulting in:

$$(4) \quad \text{Total portion of monodomains that rotate irreversibly} \cong 0.95 \times \sqrt{1 - (\mu_0 M_s / 9.5 B_{MAX})^2}.$$

Finally, the extra power loss $P_{V\text{MONO}}$ for irreversibly rotating monodomains is estimated. We multiply eq.4 with the fraction FR_{MONO} of grains that actually are monodomain, with the amount of dissipated anisotropy energy $|K|/12$ per irreversible sweep of M and with the number of magnetization cycles per second, being $2 \times$ frequency F of the applied field. We find:

$$(5) \quad P_{V\text{MONO}} \cong 0.08 \cdot F \cdot (\mu_0 M_s^2 / \mu_R) \cdot FR_{\text{MONO}} \cdot \sqrt{1 - (\mu_0 M_s / 9.5 B_{MAX})^2},$$

Eq.(5) has no solution if B_{MAX} stays below a threshold level of about 40 mT. However, as illustrated in Fig.1, the power loss term $P_{V\text{MONO}}$ rises steeply for B_{MAX} just above the threshold and becomes a constant again at $B_{MAX} \geq$ about 80 mT.

3. DISCUSSION AND CONCLUSIONS

If we neglect at 500 kHz domain wall effects, we may assume that without monodomain losses the Steinmetz coefficients of the fine grained ferrites would have been equal to that of the $16\mu\text{m}$ ferrite, so their y would have been 2.20. Figure 1 shows larger y 's of 3.25 and 2.5 for the 4 and $8\mu\text{m}$ grains, thus enabling us to estimate empirically the extra monodomain loss: in $4\mu\text{m}$ grains, a double B yields extra monodomain loss $\cong$ measured total loss $\times (2^{3.25} - 2^{2.2}) / 2^{3.25} \cong$ total loss $\times 0.5$.

Analogously, for the $8\mu\text{m}$ grains the extra monodomain loss per double B would be about 0.2 times the measured total loss. This would imply, that in Figure 1 at 100 mT the extra contribution of the monodomain loss in the $4\mu\text{m}$ ferrite amounts to about 850 mW/cm^3 , and in the $8\mu\text{m}$ ferrite to about 300 mW/cm^3 . To compare these values with eq.(5), we estimate for the fractions of monodomain grains under $3\mu\text{m}$: $FR_{\text{MONO}} \cong 0.4$ and 0.15 , respectively for the $4\mu\text{m}$ and $8\mu\text{m}$ ferrite. Taking $\mu_R = 2000$, we obtain at 500 kHz / 100 mT for the monodomain losses: $P_{V\text{MONO}} \cong 730\text{ mW/cm}^3$ in $4\mu\text{m}$ ferrite and 270 mW/cm^3 in $8\mu\text{m}$ ferrite. This fits satisfactorily with the former empirically determined extra loss contributions.

In conclusion, our simple model seems to explain qualitatively the observed anomalous induction losses in fine grains.

References

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