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The effect of material structure on the formalism of the Bertotti energy losses model

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The high requirements for magnetic circuits used in electrical equipment particularly concern the possibility of reducing energy losses. In the presented paper, the influence of the material structure on the formalism of the energy losses model is considered. It has been shown that the structure has a significant effect on the dependence between the number of magnetic domains involved in the material demagnetization and the excess magnetic field. This dependence is the basic concept of the considered model. The results presented in the paper can be used for prediction of losses in magnetic materials of different structures with satisfactory predictive errors at the design stage of magnetic circuits by means of CAD tools.

K e y w o r d s: Bertotti model, structure materials, magnetic losses

1 Introduction

The basic parameter that characterizes the possibility of using soft magnetic materials are the energy losses generated during their operation in the magnetic circuit of the electrical device. Obtaining high-efficiency equipment requires that they should be kept at the lowest possible level. At present, the Bertotti model is used for their prediction [1]. It is expressed as follows

$$P = P_h + P_c + P_{\text{exc}} \tag{1}$$

where the first component of above dependence describes the hysteresis losses associated with the currents generated by the Barkhausen jumps, the second one is related to the currents generated in the whole volume of material and the third one is related to the excess losses generated by the interaction of eddy currents originating from various time-space scales during the motion of the domain in the external magnetic field. The first component can be calculated from the material hysteresis loop, the calculation method is described in [2]. The second one is usually calculated on the basis of Maxwell's equations, the method of its calculation is presented in many works, for example, in [2]. The excess loss component can be subtracted from total losses taking into account the hysteresis and classical eddy current losses components according to $P_{\text{exc}} = P - P_c - P_h$. The energy dissipation mechanism described above demonstrates its multi-scale nature, as confirmed in the paper [3] on the application of scaling theory in the description of the energy dissipation in magnetic materials with a different structure. The issue arises when the loss component associated with excess losses P_{exc} is calculated because the knowledge of material parameters such as n_0 and H_0 is required as well as the knowledge of the relationship between the number of magnetic domains (n) in the material and the excess magnetic field: $n(H_{\text{exc}})$ and their time dependence. The values of these parameters presented in the publications very often have different values for the same materials. Calculating these losses is based on the following set of equations

$$\begin{aligned} P_{\text{exc}} &= \frac{1}{T}\int_0^T H_{\text{exc}}(t)\frac{\mathrm{d}B(t)}{\mathrm{d}t}\mathrm{d}t, \\ H_{\text{exc}}(t) &= \frac{k}{n(t)}\frac{\mathrm{d}B(t)}{\mathrm{d}t}, \text{ with } k = \sigma G S \end{aligned} \tag{2}$$

where S is the sheet cross-section area, σ is the material conductivity, G is the fraction coefficient equal to 0.1356, whereas H_{exc} is the corresponding excess magnetic field intensity. $B(t)$ is the flux density (sinusoidal waveform, excitation period T). The losses calculation can be easy carried out using the following approximation (series expansion) [1,4]

$$n = n_0 + \frac{H_{\text{exc}}}{H_0} + \frac{1}{2}\Big(\frac{H_{\text{exc}}}{H_0}\Big)^2 + \dots \tag{3}$$

The coefficients n_0 and V_0 are phenomenological model parameters that characterize the described magnetic material. The parameter n_0 is equal to the initial number of magnetic domains in the material before the magnetizing process, whereas H_0 characterizes a statistical distribution of local coercive field related to pinning centers produced by microstructure of the materials [1]. In the paper, the effect of higher terms in the series expansion (3) on the accuracy of excess loss calculation in 6.5% Si-Fe sheets is presented. The obtained results were compared to the measurement results. The experimental dependence $n(H_{\text{exc}})$, Fig.1 (b), was determined using approximation $\dfrac{\mathrm{d}B}{\mathrm{d}t}$ by the average magnetization rate $4B_{\text{m}}f$ under the assumption of sinusoidal dependence of magnetic induction on time and using the definition of the mean value of a function. In this approach, the excess

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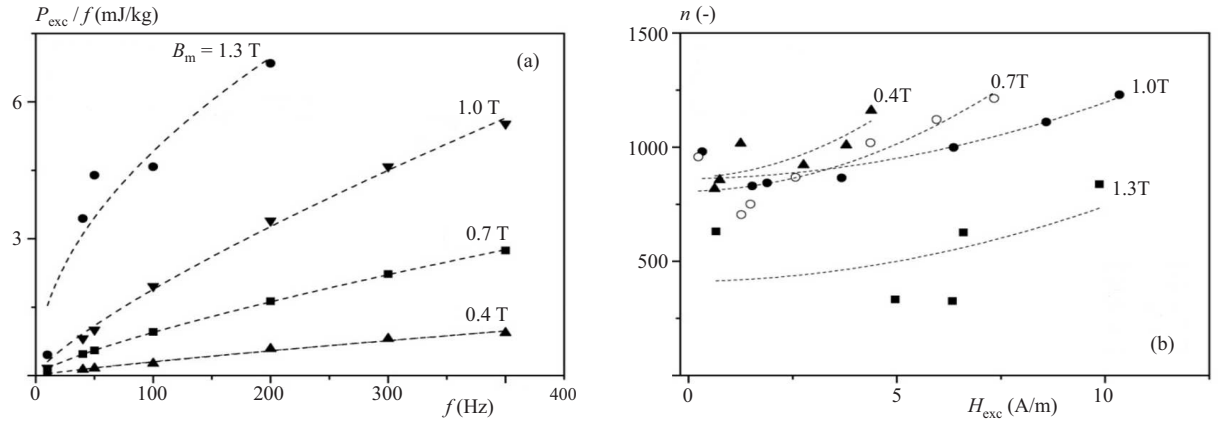

Fig. 1. The dependence of P_{exc}/f excess losses as a function of frequency for various values of maximum induction B_{m}: (a) – the dependence of the number of magnetic domains $n(H_{\mathrm{exc}})$obtained from the measured data (measurement points) with the approximation function (3) with three terms in a series (the dotted line), (b) – area of sample cross section $S = 1.75 \times 10^{-4}$ m^2, [4]

Table 1. The dependence of the material coefficient H_0 on the material structure [4], here for brevity: $h = H_{\mathrm{exc}}/H_0$, and $B' = \frac{\mathrm{d}B}{\mathrm{d}t}$

Structure	$n(H_{\mathrm{exc}})$ (-)	H_0 (A/m)	P_{exc} (W/kg)
Crystalline 3.2% Si-Fe grain oriented with rolling direction	$n = n_0 + h$	0.15	$8B_m f\left(\sqrt{kH_0B_mf} - \frac{n_0H_0}{4}\right)$ * †
Grain oriented with travers to the rolling direction	$n = (1+h)^2$	13.5	$\{h + 2h^2 + h^3 = \frac{k}{H_0}B'\}$
Crystalline 3.2% Si-Fe grain no oriented	$n = h$	0.12	$8(B_mf)^{3/2}\sqrt{kH_0}$ *
Microcrystalline 6.5% Si-Fe grain no-oriented	$n = n_0 + h + h^2$	0.2-0.4	$\{n_0h + h^2 + h^3 = \frac{k}{H_0}B'\}$
Nanocrystalline	$n = h$	2,45-2,76	$8(B_mf)^{3/2}\sqrt{kH_0}$ *
Amorphous	$n = \sqrt{h}$	0.58	$\{H_{\mathrm{exc}} = \left[H_0(kB')^2\right]^{1/3}\}$

* if: $B' \approx 4B_mf$, † providing: $n_0 << 4\sqrt{kB_mf}$

field becomes a measure of the average excess loss along the loop and the function $n(H_{\mathrm{exc}})$ provides a description of the average number of the magnetic domain in the loop [1] as follows

$$H_{\mathrm{exc}} = \frac{P_{\mathrm{exc}}}{4B_mf}$$
$$n = \frac{4kB_mf}{H_{\mathrm{exc}}} = \frac{16k(B_mf)^2}{P_{\mathrm{exc}}} \qquad (4)$$

Determination of parameters n_0 and H_0 can be made by approximation of the obtained experimental dependence with the estimate function in the form of the series expansion. It should be stressed again that $n(t)$ and H_0 are phenomenological parameters of the model characterizing the described magnetic material. In a series of papers [5-7] concerning predictions of losses in crystalline materials, the dependence between the experimental values of the excess losses and those calculated on the basis of the above model was obtained taking into account only the first two terms of development (3). For such a case, the expression for the excess losses at the sinusoidal waveform of the magnetic induction takes the simplified form (see Table 1). To calculate excess losses from the dependence (2), the material-specific dependency $n(H_{\mathrm{exc}})$ should be taken into account. The second column of Table 1 contains functions approximating this dependence obtained for different material structure. The third column contains a system of (2), taking into account this relationship.

In this paper, it has been shown that predictions of the excess losses in magnetic materials of a different structure than crystalline should take into account higher-order nonlinear terms of the expansion $n\big(H_{\mathrm{exc}}\big)$ in the series as well.

2 Measuring system

For the tested 6.5% Si-Fe material, the measurements of the energy loss have been carried out on samples in the form of sheets with the dimensions $500 \times 500 \times 0.5$ mm

Table 2. Parameters n_0 and V_0 of the approximation function (3) at different values of maximum induction B_m for 6.5% Si 10JNEX 900 [4]

B_m (T)	n_0 ($1/\mathrm{m}^2$)	SD	H_0 (A/m)	error	R
1.3	411	159	0.404	0.195	0.033
1.0	861	31	0.401	0.038	0.829
0.7	806	50	0.258	0.032	0.732
0.4	866	47	0.205	0.037	0.586

using a Single Sheet Tester Device cooperating with the measurement stand MAG-RJJ-2 [8], whose role was to maintain the sinusoidal waveform of the flux density in the sample. The measurements were carried out accordance with the international standard IEC 404-3 [9]. The relative error of loss measurement was equal to 1.5%.

3 Results and discussion

In this paper, the results of the energy loss predictions obtained for the commercial 10JNEX900 sheet with 6.5% silicon content are presented. The component P_exc of total losses is calculated based on the set of (2). The relation $n(H_\mathrm{exc})$ is obtained using (4) for data obtained from measurements at different values of magnetic induction and frequency magnetic field. Satisfactory accordance between theoretical and experimental dependence is obtained for the three words in the series expansion (see Fig. 1). In the range of induction changes from 0.4 T to 1 T, in which the energy dissipation is mainly related to the moving domain walls under external magnetic field, the error between experimental data and obtained from calculations does not exceed 4% The influence of the domain rotation as the mechanism of energy dissipation in material above 1.3 T, results in an increase of error up to 20% (see Tab. 2 and Fig. 1). In previous works on the presented model applied to describe excess losses in materials with silicon content 6.5% no satisfactory results were obtained because only two terms were taken into account in the series expansion (3), [4].

4 Conclusions

Summing up to this point, the practical use of the Bertotti model to describe the excess losses in magnetic material requires the knowledge of the function $n(H_\mathrm{exc})$ depending on the microstructure of the examined material and the domain structure. Using this dependence to predict the energy losses for 6.5% Si-Fe requires taking into account nonlinear terms in the expansion of this function which allows one to obtain the prediction error of those losses below 4%. The above situation takes place for induction up to 1T, when the dominant mechanism of energy dissipation is the movement of domain walls. In saturation conditions, where the dominant mechanism is the rotation of magnetic domains, the prediction error not exceeding 20%. It is possible to use the presented results in the engineering practice at the design stage of magnetic induction circuits by means of CAD tools [10].

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