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Hysteresis and Excess Power Loss Components Properties in Grain-Oriented Electrical Sheets

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The most popular loss model for electrical steel sheets is the three-component model, which divides the specific total loss into hysteresis, classical eddy current, and excess components. The latter component is defined as the difference between the measured loss and the loss calculated using Maxwell's equations. The origin of the excess component has been a subject of debate for many years. Initially, it was associated with hysteresis loss and later with micro-eddy currents. Furthermore, the interdependence of the components complicates their modeling. This paper presents the results of research and analysis of loss components for the three-component model, taking into account the phenomenon of magnetic anisotropy. The studies were conducted on samples of conventional grain-oriented electrical steel sheet for several selected magnetization directions. The results indicate a correlation between the hysteresis and excess components for different magnetization directions. The paper proposes combining both components in a loss model for electrical sheets.

topics: specific total loss, magnetic anisotropy, hysteresis and excess loss components

1. Introduction

For over a century, scientists have been modeling the phenomenon of magnetic loss caused by the magnetization of magnetic materials. Due to the complex physical process of magnetization in these materials, statistical models of loss have been developed [1]. Despite the imperfections in describing physical transformations, they are successfully used in the design of magnetic cores in electrical devices.

One of the most popular statistical models is the three-component model of specific total loss P_S [2], which distinguishes the hysteresis P_h, the classical eddy current P_{ce}, and the excess P_{ex} component. The origin of P_{ex} loss has been discussed since the introduction of grain-oriented electrical steel sheets. Initially, this loss component was associated with the hysteresis component [3–5]; currently it is understood to be induced by eddy currents, which arise from micro-eddy currents resulting from the motion of domain walls [2, 6]. Hence, the division into dynamic loss consisting of classical eddy current component (calculated from Maxwell's equations), excess loss (micro-eddy currents), and so-called static loss associated with the hysteresis component, which can be determined experimentally by extrapolation to zero frequency. The interdependence between the three loss components is generally recognized. As the magnetic flux density rate of change increases, eddy currents increase, causing magnetic flux displacement (skin effect) and changing the flux density distribution in the sheet [3]. As a result, the energy of the hysteresis loss component changes with increasing magnetization frequency. Similar interdependencies also occur for the excess component. Changing the domain structure results in a change in the generation of micro-eddy currents and therefore affects both the hysteresis and excess components. There is no doubt that the three-component model is very helpful in optimizing loss in electrical steel sheets, for example, by enabling loss optimization through the selection of the chemical composition of the SiFe alloy [7] or the introduction of mechanical surface treatment, e.g., using balls [8] or laser [9].

In papers [10, 11], an analysis of the correlation between the hysteresis and excess components for the angular properties of loss in electrical steel sheets is presented. In works [12, 13], models of directional loss combining the hysteresis and excess components were presented. In [12], the orientation distribution function (ODF) was used, while in [13], the sigmoid function was used. This paper presents the results of the analysis of both loss components, indicating their close correlation resulting from changes in the domain structure.

2. Experimental results

This paper uses the results of total loss measurements of conventional grain-oriented electrical steel sheet grade M120-27S magnetized along selected directions measured relative to the rolling direction. Samples were prepared from a single sheet, cut at angles of 0°, 30°, 45°, 60°, and 90° relative to the rolling direction. Measurements were performed using a custom single-sheet tester with square samples with a side length of 100 mm . The system was equipped with leakage flux compensation. The form factor (FF) of the sinusoidal shape of magnetic flux was set to be less than or equal to 0.5%, and the total harmonic distortion (THD) was set to be $\leq 5\%$ over the entire range of measured frequencies and flux densities. The specific total loss P_S was measured in the frequency range from 5 to 100 Hz. The loss measurement results allowed for the separation of loss into components, appropriately performed for a three-component model in a simplified form [2] described by

$$W_S = \frac{P_S}{f} = C_h + C_{ce} f + C_{ex}\sqrt{f}, \tag{1}$$

where f is the frequency, C_h and C_{ex} are, respectively, the hysteresis and the excess loss coefficients, C_{ce} is the classical eddy current loss coefficient that can be calculated as $C_{ce} = \pi^2 d^2 B_p^2/(6\rho\gamma)$, d is the lamination thickness, ρ is the electrical resistivity, and γ is the material density.

The P_S loss separation procedure is presented in detail in [10, 12]. It should be emphasized that the calculated coefficients C_h and C_{ex} include the factor B_p^α as in the three-component model [2]. The reason for this procedure is that the exponent of peak flux density B_p is not constant. As shown in [12, 14], the dependencies of the hysteresis and excess components, above the maximum magnetic permeability, deviate from a simple power law. Assuming a constant value of the power exponent for both components causes significant errors in the calculation of total losses [13].

3. Results and discussions

The separation of losses and the calculation of loss components enabled the determination of the excess loss coefficient η_{ex} [3]. The coefficient η_{ex} describes the multiplicity of the excess loss P_{ex} over the classical eddy current loss P_{ce}. It is defined as

$$\eta_{ex} = \frac{P_S - P_h}{P_{ce}} = \frac{P_{ce} + P_{ex}}{P_{ce}}. \tag{2}$$

Factor η_{ex} takes into account phenomena such as the magnetic domain structure, magnetic anisotropy, and the thickness of the analyzed electrical steel sheets. It can also be determined for magnetization directions other than 0° [12]. Figure 1 shows the dependence of the excess loss factor for selected magnetization directions at the flux density value of 1.2 T.

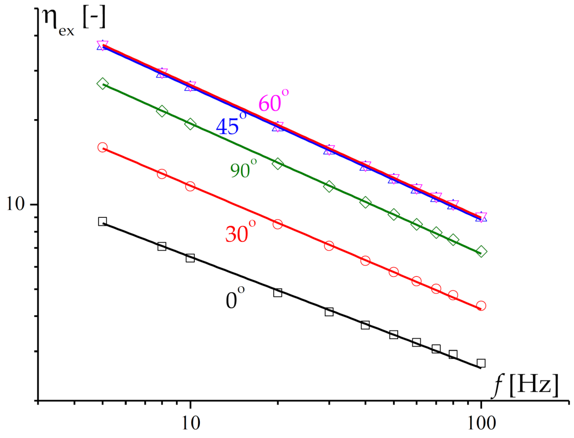

Fig. 1. Variation of excess loss factor η_{ex} for electrical sheet M120-27S ES with frequency for peak flux density $B_p = 1.2$ T on a log–log diagram for magnetization angles 0°, 30°, 45°, 60°, and 90°.

As could be expected from (2), as $P_{ce} \to 0$ for f $\to 0$, the excess loss factor η_{ex} tends to ∞. The tendency of the η_{ex} coefficient to ∞, shown in Fig. 1, exhibits a different character for different values of flux density. This implies the occurrence of excess loss at very low frequencies for which the hysteresis loss is determined, and significant values of the η_{ex} coefficient result from the mathematical relationship (2).

The relationships shown in Fig. 1 were approximated by an inverse power function with offset $\mathrm{f}(f) = 1 + a\, f^b$ resulting from (2). The exponents of the power function with an offset fit for all selected magnetization directions are equal to -0.5. The directional coefficients describe anisotropic properties. It should be noted that the data for directions 45° and 60° are limited to a flux density of 1.2 T due to the imposed limit of FF coefficients $\leq 0.5\%$ and THD coefficient $\leq 5\%$.

In a similar way to (2), the hysteresis loss coefficient η_h can be presented by

$$\eta_h = \frac{P_S - P_{ex}}{P_{ce}} = \frac{P_{ce} + P_h}{P_{ce}}. \tag{3}$$

Figure 2 shows the characteristics of $\eta_h = \mathrm{f}(f)$, similarly to Fig. 1. Moreover, Fig. 3 shows the dependencies of the directional coefficients a of the hysteresis loss coefficients (3) for three selected magnetization directions.

Similarly to the case of η_{ex}, as $P_{ce} \to 0$ for $f \to 0$, the hysteresis loss factor η_h tends to ∞, and the obtained dependencies shown in Fig. 2 can be approximated by an inverse power function with an offset $\mathrm{f}(f) = 1 + a\, f^b$ resulting from (3). The exponent of the power function b remains constant for all selected magnetization directions and is equal

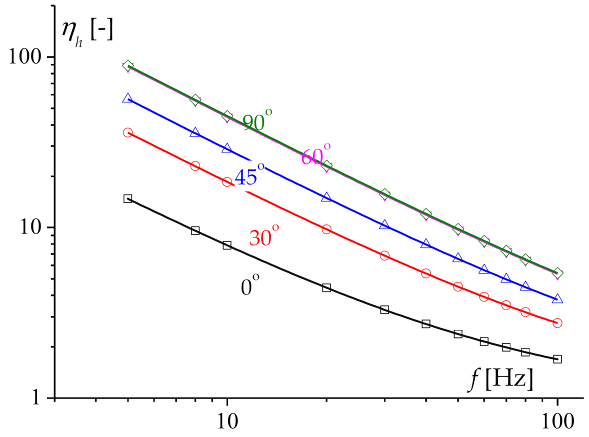

Fig. 2. Variation of hysteresis loss factor η_h for electrical steel sheet grade M120-27S with frequency for peak flux density $B_p = 1.2$ T on a log–log diagram for magnetization angles 0°, 30°, 45°, 60°, and 90°.

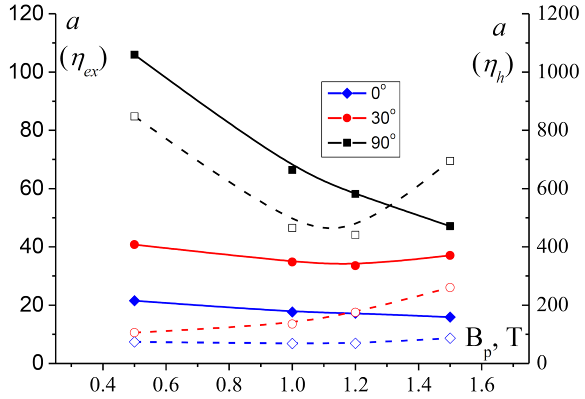

Fig. 3. Dependence of the directional coefficients a of the function $1 + af^b$ of the coefficients η_{ex} (fulfilled symbols) and η_h (empty symbols) for selected magnetization directions 0°, 30°, and 90°.

to −1. The tendency of the coefficient η_h to ∞, shown in Fig. 2, exhibits a different character for different values of flux density. However, the directional coefficients a describing the anisotropic properties of the coefficients η_{ex} (see (2)) and η_h (see (3)) are presented for three magnetization directions in Fig. 3.

As can be seen in Fig. 3, the directional coefficient a for the 0° and 90° directions continuously decreases in the studied range to $B_p = 1.5$ T. For the remaining magnetization directions, the coefficient a decreases for flux density to a value of ≈ 1.0 T and then increases. The nature of these changes is related to the significant ordering of magnetic domains (above the maximum values of relative magnetic permeability) and the phenomenon of magnetic anisotropy. A change in the magnetization direction causes a different, consistent with Neel's phase theory [15], movement of domain walls, associated with the domain ordering in the opposite direction, and an increase in micro-eddy currents, to which the excess loss component refers.

As shown in Fig. 3, the directional coefficients for the excess and hysteresis loss coefficients, calculated from (2) and (3), respectively, exhibit a significant similarity for different magnetization angles. The visible differences in the directional coefficients a for η_{ex} and η_h may result from the shielding effect of micro-eddy currents on the irreversible motion of domain walls, characteristic of hysteresis loss. After reaching maximum magnetic permeability ≈ 1 T, a change in the local magnetic field disrupts the motion of the surrounding domain walls, resulting in an increase in hysteresis loss. This effect is particularly visible for the 90° direction, but is also seen for the other magnetization directions.

A similar relationship can be observed in Fig. 4, which shows the contribution of the hysteresis component depending on the contribution of the excess component to the total loss.

As shown in Fig. 4, with increasing frequency, the share of hysteresis loss decreases and the share of excess loss increases, clearly indicating the relationship between excess loss and eddy current generation. For the 0° direction, the share of hysteresis loss in the total loss decreases more slowly up to about 30 Hz. Above 30 Hz, the share of hysteresis loss decreases drastically, with the share of excess loss remaining almost unchanged. This is related to the phenomenon of domain size change in the range from 0 to 30 Hz [16] to the value generated by the domain system occurring under static conditions (parallel to the eddy current component on the $P_S/f = \mathrm{f}(f)$ characteristic). Due to the different magnetization phase for magnetically difficult directions [15], the effect of domain size change is not visible, as for 0°, and the share of hysteresis component is larger. An increase in the share of the component no longer causes a rapid decrease in the share of the hysteresis component. For the 30° direction, which is not shown, the relationship is very similar. For the 45° and 60° directions, the dependence of the hysteresis component share on the excess component share in the total loss is linear, similar to that shown in Fig. 4b for the 90° direction. It is more difficult to distinguish the change in the component share for the two frequency ranges up to 30 Hz and above.

4. Summary

This paper presents an analysis of the components of total loss occurring in the grain-oriented electrical sheet M120-27S. The phenomenon was qualitatively analyzed. The obtained results were used to analyze the relationships between the components of total loss (hysteresis, classic eddy current, and excess components) for selected

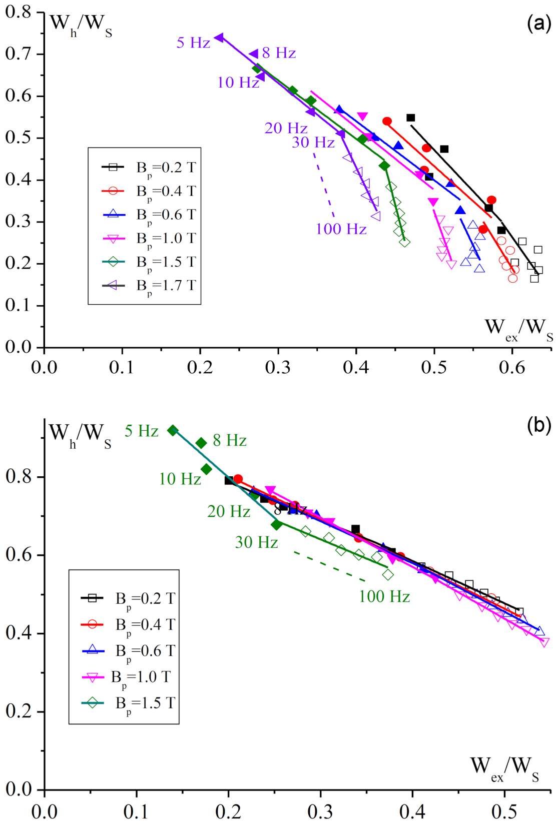

Fig. 4. The share of the hysteresis component in total loss as a function of the share of the excess component in total loss for electrical steel sheet grade M120-27S for magnetization angles (a) 0° and (b) 90°. Solid symbols indicate points for the frequency range from 5 to 30 Hz, and empty symbols indicate points for the range from 40 to 100 Hz.

magnetization directions. The total loss for each of the selected magnetization directions was separated [10, 12] according to the principle that hysteresis loss is the loss determined by extrapolation to a frequency of 0 Hz and varies directly with frequency. For extremely low frequencies and magnetization at 0° direction it is assumed that the energy of hysteresis loss is generated by a 180° domain system [16, 18]. At this assumption the hysteresis loss component stays proportional to frequency also for magnetisation at 50 Hz. The source of excess and hysteresis losses is domain motion. Both components also show a strong dependence on the magnetization direction [11, 13].

The coefficients η_{ex} (2) and η_h (3) take into account, among others, phenomena such as the magnetic domain structure, magnetic anisotropy, and the thickness of the analyzed electrical steel sheet. Figures 1 and 2 present the dependence of the coefficients η_{ex} and η_h on frequency. Both coefficients are characterized by different asymptotes depending on the flux density and the direction of magnetization. This indicates the presence of an additional loss component at frequencies close to 0 Hz, which may be associated with the generation of excess loss. In the case of the coefficient η_{ex}, it indicates the existence of a hysteresis component [10]. The directional properties confirm the relationships presented in Fig. 3. The directional coefficients for both coefficients show a strong dependence on the magnetization direction, and the increase in hysteresis loss for magnetically difficult directions affects the shielding effect of micro-eddy currents.

The theorems put forward years ago about the variation of hysteresis loss with frequency, for example by Bozorth or in [3] and postulated later in [18–20], seem to be correct. It was proposed to introduce an additional frequency-dependent component of hysteresis loss. For example, in [19, 20], the component of hysteresis loss was determined as a function of the magnetization frequency. In fact, Bertotti [21] also demonstrated a correlation between the excess and hysteresis components.

5. Conclusions

The analysis of the hysteresis and excess loss components presented in this paper, taking into account directional properties, indicates a strong interdependence between them. The introduced hysteresis loss coefficient indicates both differences in the mechanism of generated loss and the common source, i.e., domain wall motion. As frequency and flux density increase, micro-eddy currents alter the local magnetic field distribution, resulting in a faster increase in the hysteresis component than would be expected from a simple power law, especially for magnetically challenging directions.

The analytical results presented in this paper confirm the validity of the proposed two-component model combining hysteresis and excess components, taking into account the phenomenon of magnetic anisotropy.

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