ENERGY LOSSES PREDICTION IN NON-ORIENTED SILICON IRON SHEETS

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Key words: Non-oriented silicon iron, Energy losses, Magnetic objects, Energy losses prediction, Excess losses, Magnetizing processes

We report an investigation and a theoretical assessment of power losses prediction in non-oriented silicon iron sheets (NO FeSi) M800-65A industrial type, cut longitudinally and transversally to the rolling direction. The loss behaviour of this material was studied as function of frequency in the range of 5 Hz to 200 Hz at a given magnetic polarization (*J*) of 0.5 T and 1 T. Using the concept of loss separation for the data analysis, in the approximation of linear magnetization law and low frequency limit, it can be considered that the excess losses can be quantitatively assessed within the theoretical framework of the statistical loss model based on magnetic object theory.

1. INTRODUCTION

Non-oriented (NO) silicon iron alloys are soft magnetic materials with an approximately anisotropic grain texture. They are used in the fabrication of medium and high power rotating machines, and for that it is necessary to develop magnetic circuit for electrical machines with efficiency higher than 95%, not only to save energy, but to avoid overheating and shortening of the machine lifetime. Improvement of the quality of the sheets can be realized by controlling a number of structural parameters: impurities, grain size and crystallographic texture, residual and applied stresses etc. The NO FeSi sheets are produced accordingly with the standards IEC 60404-8-2 and 60404-8-4 and are manufactured in different qualities defined by the amount of silicon in the alloy. The percentage of silicon in the alloy can vary from 1 to 3.7 %, and to prevent the aging of the material is used aluminium (0.2÷0.8 %). To increase the electrical resistance of the sheets there are usually added small quantities of manganese (0.1÷0.3 %) [1, 2].

Magnetic cores of electrical machines are practically subjected to a non-sinusoidal magnetic flux density, generated by the pulsating waveforms of the magnetic induction in the teeth of the stator core or by the driving circuit, due to the pulsewidth modulated (PWM) voltages. Data sheets from manufacturers

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present the energy losses values of the material only at industrial frequency (50 Hz/60 Hz) for selected peak magnetic flux density (J_p) values [1]. These data provide us poor information (*e.g.* P_{tot} = 6.74 W/kg at J = 1.5 T, f = 50 Hz, anisotropy of loss 3%, μ_r = 1 900 [3]) for a basic design of electromagnetic devices, used in predictive purposes. One can improve it with the frequency characterisation and the theoretical losses model. The model for electromagnetic energy losses prediction based on the statistical theory can be used for NO FeSi sheet under sinusoidal and non-sinusoidal induction waveform, in case that the working frequency is low enough to ensure uniform magnetic flux penetration [4].

2. ENERGY LOSSES SEPARATION METHOD

The total energy losses can be decomposed into the sum of hysteresis, classical and excess losses components. This separation allows to individually treat loss mechanisms occurring on different space-time scales, as they were independent to each other.

The hysteresis losses are generated by fine-scale instabilities and can be analyzed by coercivity mechanisms.

In the case of eddy losses (classical) generated by eddy currents, the sample geometry is important. The material is treated like a homogenous medium.

The direct consequence of the magnetic domains structure of the material is the excess losses which are very difficult to be determined, because of the great variety of domain structures. One prefers to determine this type of losses only through mathematical methods.

The energy loss separation was made, using for the calculation of classical energy losses (W_{cl}), in the approximation of linear magnetization and low frequency limit [2, 5], the following relation:

$$W_{cl} = \frac{\pi^2}{6} \frac{\sigma J_p^2 d^2}{\rho} f, \tag{1}$$

where σ is the electrical conductivity, d is the thickness of the sheet, f is the frequency and ρ is the density of the material.

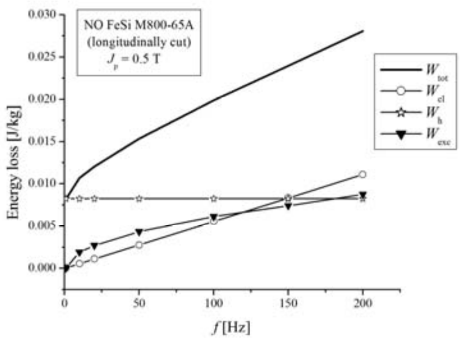
Further, the sum of excess losses W_{exc} and hysteresis losses W_h is:

$$W_{diff} = W_{tot} - W_{cl} = W_h + W_{exc}. \tag{2}$$

Making a graphical extrapolation of W_{diff} to zero, the W_h and therefore the W_{exc}, have been determined [5]. Hysteresis energy losses and excess losses are quantities directly related to the eddy current paths closely surrounding the active domain walls.

3. **EXPERIMENTAL RESULTS**

In this paper two NO FeSi (M800-65A) sheets of 280×30 mm^2 are investigated. One sample was cut longitudinally, and the other transversally to the rolling direction. The physical properties of this material are: thickness d = 0.65 mm, density ρ = 7 800 kg/m^3, electrical conductivity $\sigma = 48 \cdot 10^8$ S/m, saturation polarization J_s = 1.8 T. The samples were characterized between 0 Hz and 200 Hz using an industrial Single Sheet Tester (Brockhaus Messtechnik), which is a device for fast measurements. The Brockhaus Single Sheet Tester offers an AC frequency characterisation and provides the hysteresis cycle, the relative magnetic permeability and the total power losses data.



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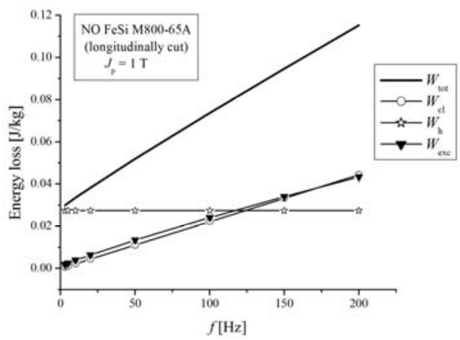

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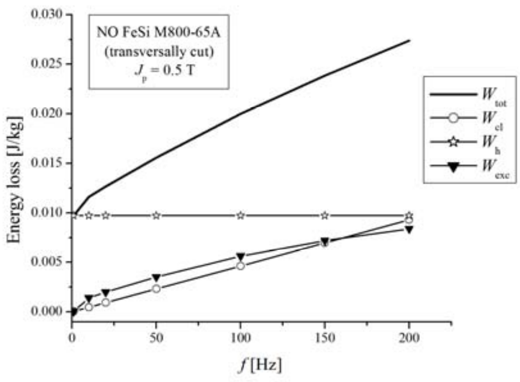
Fig. 1 – Specific energy loss and its components in the case of NO FeSi sheet (longitudinally cut) versus magnetizing frequency at peak polarization: a) J_p = 0.5 T; b) J_p = 1 T.

In Fig. 1 and Fig. 2 the variations of W_{tot} versus frequency f were determined through experimental procedure. The variations of W_{cl} were calculated with (1), W_h and W_{exc} were obtained as presented in chapter 2.

The dependences $J(H)$, measured on rolling (RD) and transversal (TD) directions and presented in the data sheets [3], have so small differences, that the manufacturers consider this type of alloy as isotropic one. In this paper, as one can see in Fig. 1 and Fig. 2, in the case of the energy losses can be observed some differences between the values, measured on RD and TD directions, so that an analysis of losses, on the easy and hard axes, was considered necesary.



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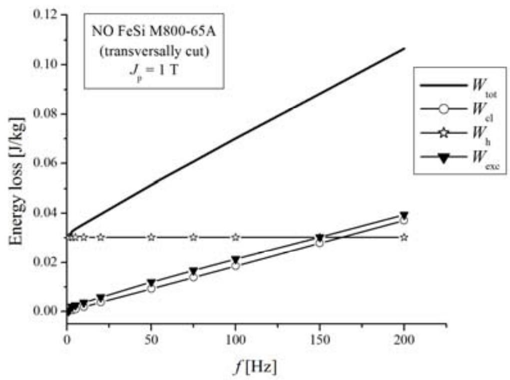

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Fig. 2 – Specific energy loss and its components in the case of NO FeSi sheet (transversally cut) versus magnetizing frequency at peak polarization a) J_p = 0.5 T; b) J_p = 1 T.

One can notice that with the increase of peak polarization the energy loss shapes tend to have a linear variation and the most important loss is the hysteresis one (W_h) at least up to 150 Hz [6]. Also, because the non-oriented FeSi alloys do not have such a pronounced value of magnetic anisotropy, there are no significant differences (more evident in the case of high magnetic polarization and high frequencies) between the losses values, measured in the case of longitudinally and transversally cut sheets.

4. STATISTICAL INTERPRETATION OF EXCESS LOSSES

The model for electromagnetic energy loss prediction based on the statistical theory of losses [5, 7] can be used for soft magnetic alloys if the working frequency is sufficiently low to ensure an uniform magnetic flux penetration. The model relies on the physically based idea of loss separation.

The statistical model considers that the large-scale pattern of magnetic domains can be described in terms of the dynamics of *n* statistically independent magnetic objects (MO). A magnetic object represents a group of neighboring interacting domain walls and reduces the losses problem to the investigation of the main physical properties of *n* as a function of frequency, peak polarization and material microstructure. This theory reduces the dependence of excess energy losses on both peak polarization and measurement frequency to a common mechanism [5, 8].

The physical mechanism that generates excess losses in soft magnetic materials is based on the competition between the applied external magnetic field and the local counterfields, highly inhomogeneous, determined by the eddy currents and microstructural interactions [5].

For each value of the average polarization rate the magnetization process in a given cross section of the sample can be described in terms of *n* simultaneously active magnetic objects. The dynamic behaviour of a single MO is ruled, in this case, by a linear dependence of the excess dynamic field $H_{exc} \propto \dot{\Phi}$ acting on the MO, where $H_{exc} = \frac{p_{exc}}{\dot{J}}$, $\dot{\Phi}$ is the magnetic flux rate of change correspondingly provided by the MO, p_{exc} is the density of excess power loss, J is the magnetic polarization and the proportionality constant is determined by the damping effect of eddy currents [9−12]. When there are *n* simultaneously active MO's, $\dot{\Phi}$ must be, on the average, a fraction $1/n$ of the total flux rate $S\dot{J}$ imposed to the sample (S is the cross-sectional area of the probe), so that a relationship of the form $H_{exc} \propto 1/n$ is expected, which actually turns out to be [10]

$$H_{exc} = \frac{p_{exc}}{\dot{J}} = \frac{p_{exc}}{4J_p f} = \frac{H_w}{n}, \qquad (3)$$

where

$$H_w = 4\sigma G^{(w)} S J_p f \,, \tag{4}$$

with a value of the dimensionless coefficient $G^{(w)} = \dfrac{4}{\pi^3}\sum_k \dfrac{1}{(2k+1)^3} = 0.1356.$

The main property of the quantity n appearing in (3) is that it is expected to be a function $n(H_{exc}, \{P\})$ of the excess field H_{exc} and a set of $\{P\}$ parameters characterizing the microstructure and the domain structure of the material.

Some mathematical interpolations proved that the NO FeSi alloy, along both longitudinal and transversal directions, obeys a simple linear law:

$$n(H_{exc}, \{P\}) = n_0 + \frac{H_{exc}}{H_0} \,, \tag{5}$$

where the microstructural information is now carried by n_0, which represents the limiting number of simultaneously active MO's when $f \to 0$ and by the magnetic field H_0. The phenomenological parameters (n_0, H_0) can be determined by a linear interpolation of the graphical dependence $n(H_{exc})$ (Fig. 3).

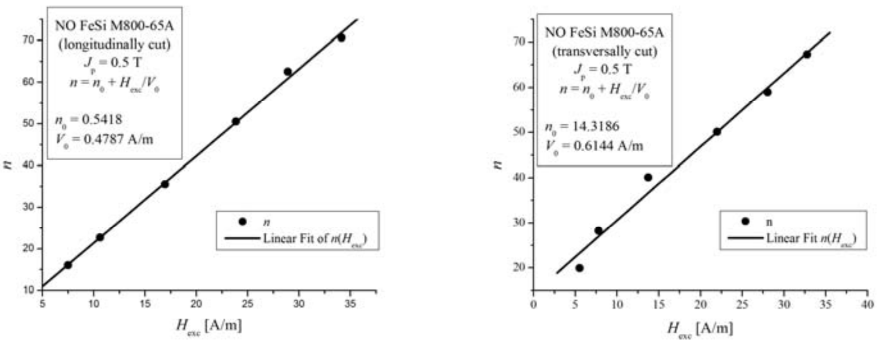

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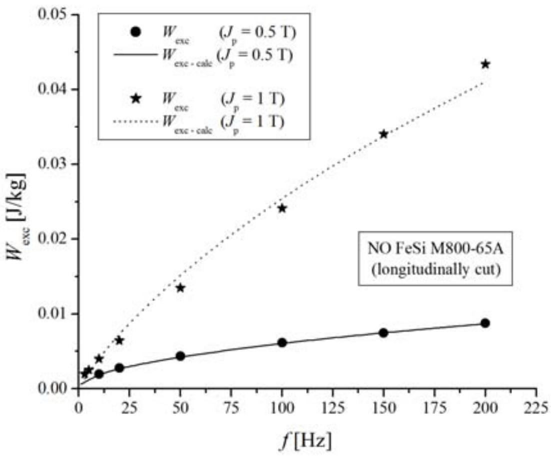
Fig. 3 – Number of active magnetic objects n versus the dynamic field H_{exc} at peak polarization J_p = 0.5 T: a) longitudinally (n_0 = 0.5418, H_0 = 0.4787 A/m); b) transversally (n_0 = 14.3186, H_0 = 0.6144 A/m) cut samples). In the case of J_p = 1 T the values are: n_0 = 27.206, H_0 = 2.422 A/m (longitudinally cut sample) and n_0 = 27.545, H_0 = 2.036 A/m (transversally cut sample).

The knowledge of n_0 and H_0 permits one to predict through (6) the behavior of excess losses (W_{exc}):

$$W_{exc-calc} = 2J_p\left(\sqrt{4H_0H_w + (n_0H_0)^2} - n_0H_0\right) \tag{6}$$

and, by using the parameters identified before, the shapes of the determined W_{exc} are presented in Fig. 4.



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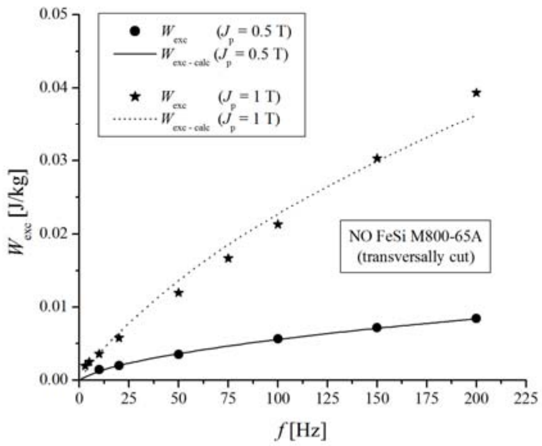

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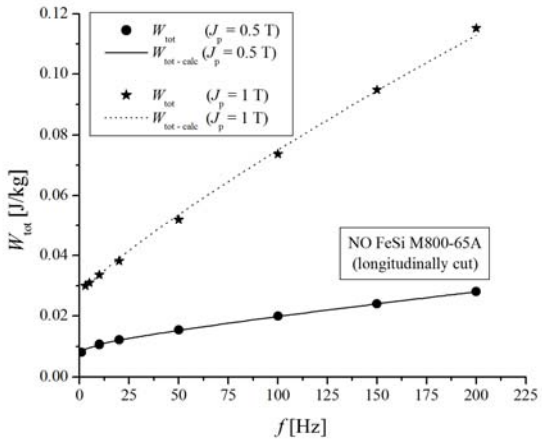
Fig. 4 – Comparison between the experimental values (W_{exc}) and the predicted ($W_{exc\text{-}calc}$) behaviour of excess losses in NO FeSi laminations: a) longitudinally cut samples; b) transversally cut samples.

The theoretically predicted total loss ($W_{tot\text{-}calc}$) is therefore obtained through:

$$W_{tot-calc} = W_{h-exp} + W_{cl} + W_{exc-calc}, \tag{7}$$

where $W_{h\text{-}exp}$ has the value of W_h, determined in chapter 2 (Fig. 5).



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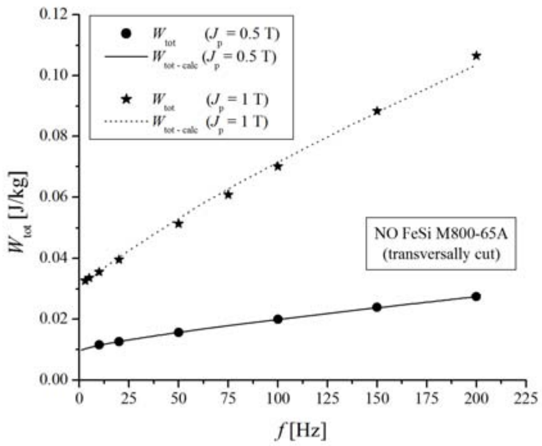

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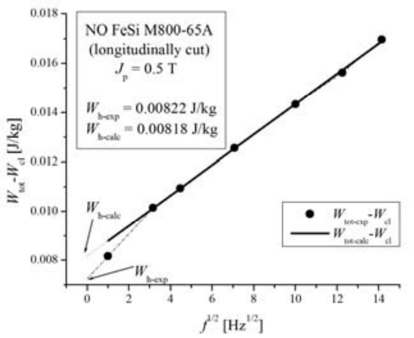
Fig. 5 – Comparison between the experimental values (W_{tot}) and the predicted ($W_{tot\text{-}calc}$) behaviour of total losses in NO FeSi laminations: a) longitudinally cut samples; b) transversally cut samples.

Also, based on the theoretical values of the total loss ($W_{tot\text{-}calc}$) and the exactly calculated classical loss (W_{cl}), one can perform an analytical determination of hysteresis loss ($W_{h\text{-}calc}$), which can be compared to the values obtained from the experimental measurements (Fig. 6).



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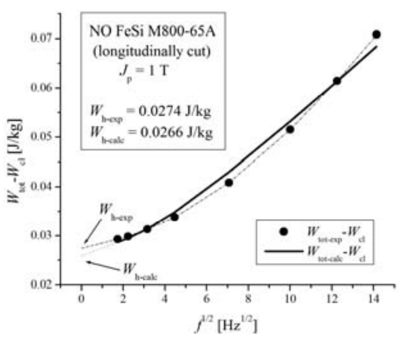

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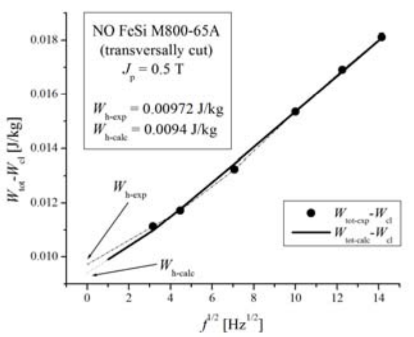

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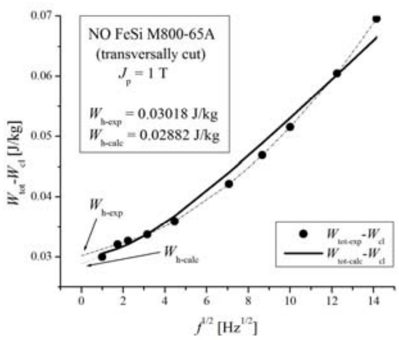

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Fig. 6 – Examples of experimental and predicted dependences of the quantity $W_{diff} = W_{tot} - W_{cl} = W_h + W_{exc}$ on the square root of frequency in NO FeSi laminations. The zero-frequency value $W_{diff}(0) = W_h$ is obtained by a graphical extrapolation. (a, b – longitudinally cut samples at $J_p = 0.5$, 1 T and c, d – transversally cut samples at $J_p = 0.5$ and 1 T).

5. **CONCLUSIONS**

The theoretical interpretation of the experimental results on energy excess losses in soft magnetic materials provides a promising convenient tool to look into the connection between dynamic losses and microstructure of samples. The values obtained through analytical expressions are in a good accord with the experimental ones.

The statistical model is a very accurate method for the prediction of the excess energy losses in soft magnetic alloys. The theoretical interpretation of the experimental results on power losses in soft materials has shown that the function $n(H_{exc}, \{P\})$ provides a promising tool to look into the connection between dynamic losses and microstructure of soft materials. In several cases, a single function $n(H_{exc}, \{P\})$ can be associated with a given material and the linear law is the easiest one. This law is very adequate for NO FeSi alloys. The hard magnetization axis has a pronounced contribution on the values of W_h in the case of transversally cut sample, which are higher that in the case of the sheets cut parallel to the rolling direction, because the spin magnetic moments must align to the direction of the external field, which is applied horizontally.

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