Modelling minor hysteresis loops of high silicon steel using the modified Jiles-Atherton approach

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Introduction

Accurate description of minor hysteresis loops is important from engineering point of view. There is a number of available descriptions of ferromagnetic hysteresis [1]. In the paper the issue was considered for a hybrid model combining ideas included in the Jiles-Atherton description [2] and the product Preisach model [3-5]. The sample material was a state-of-the-art core material: micro-crystalline non-oriented 6,5 % wt. Si steel produced by JFE Steel Corporation [6,7].

The modified Jiles-Atherton model

The Jiles-Atherton description was developed on physical premises concerning domain wall motion within the ferromagnetic material. In the present paper the model equations were slightly modified to address the issue of description of reversible magnetization processes. The modifed approach helps to explain the ambiguities in the description noticed by some model users [8], including the model authors themselves [9,10]. The problems with the correct description of reversibility in the context of another hysteresis model are also discussed elsewhere [11,12].

In the paper the issue has been addressed borrowing the idea introduced originally in the product Preisach model [3-5]. It is assumed that the total susceptibility may be expressed as the sum of irreversible and reverisble contributions, modulated with a function dependent on the level of magnetization. The assumed form of the function is $R(m) = 1 - m^2$, where m is the relative magnetization, $m = M_{TIP} / M_S$ (M_{TIP} is the magnetization of a symmetric minor loop tip, whereas M_S is saturation magnetization).

(1) $$\frac{dM}{dH} = R(m)\left[\beta + \frac{dM_{irr}}{dH}\right].$$

The irreversible differential susceptibility may be derived from the basic model JA equation:

(2) $$\frac{dM_{irr}}{dH_e} = \frac{\delta_M \left(M_{an} - M_{irr}\right)}{k\delta},$$

where the effective field H_e is given as $H_e = H + \alpha M$, M_{an} and M_{irr} are the anhysteretic and irreversible magnetization, respectively, δ is the sign of dH/dt (for the simple model) or dB/dt (for the inverse model), k is one of model parameters, whereas δ_M is introduced to remove negative differential susceptibilities after a field reversal [13]

(3) $$\delta_M = 0{,}5\left[1 + sign\left[\left(M_{an} - M_{irr}\right)\frac{dH}{dt}\right]\right].$$

It is assumed that the anhysteretic magnetization is given with the Brillouin function, where $J = 1$ [14]:

(4) $$M_{an} = M_s\left[\frac{(2J+1)}{2J}\coth\frac{(2J+1)}{2J}\frac{H_e}{a} - \frac{1}{2J}\coth\frac{1}{2J}\frac{H_e}{a}\right]$$

The value of new parameter β related to reversible properties of the examined material may be easily recovered from a low amplitude minor loop using the Rayleigh model equation, cf. Fig. 1:

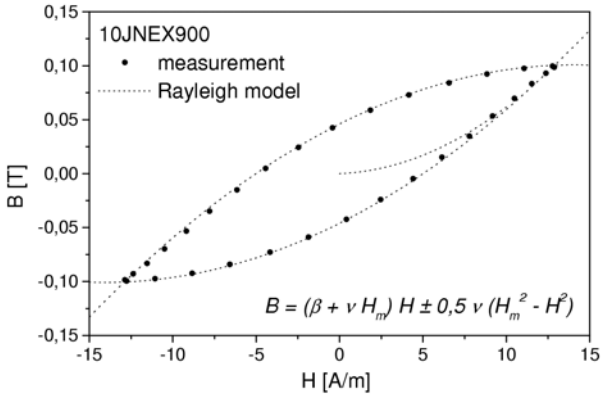

Fig.1. Determination of value of parameter β from a minor loop

The modified model has five parameters: α, β, a, k and M_s. Their values may be determined using the robust "branch-and-bound" estimation algorithm, described in detail in [15]. The idea behind the estimation method is basically the same as in the well-known fixed point method [16,17], applied simultaneously in five dimensions. The bounds for model parameters were similar to those discussed previously [15, 18]. The estimate of parameter β obtained from the Rayleigh model was allowed to vary within the bounds ± 10 % to take into account the possible effect of measurement noise.

The model equations were transformed to the following form, appropriate for the determination of M and H under the conditions of sine-B excitation, required by IEC 404-3 standard [19]:

(5) $$\frac{dM}{dB} = \frac{R(m)\left[\beta k\delta + \delta_M\left(M_{an} - M_{irr}\right)\right]}{\mu_0\left[k\delta\left[1 + R(m)\beta\right] + (1-\alpha)R(m)\delta_M\left(M_{an} - M_{irr}\right)\right]}$$

It was found that the following set of model parameters can yield a modelled major hysteresis loop, which reasonably well approximates the measured one: $\alpha = 1{,}6 \times 10^{-5}$ [-], a = 11,2 [A/m], $\beta = 6{,}9 \times 10^{-4}$ [H/m], k = 27,9 [A/m], $M_s = 1{,}28 \times 10^6$ [A/m], cf. Fig. 2.

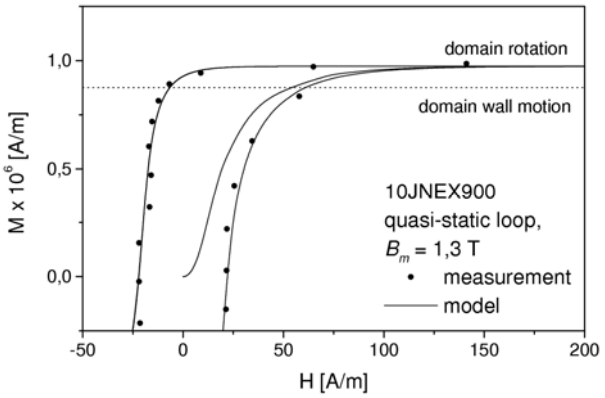

Fig.2. Measured and modelled quasi-static hysteresis loops for 6,5 % wt. Si NO steel sheet. Dotted line at B_m = 1,1 [T] denotes symbolically the border between two regions of different prevalent magnetization mechanisms

The fitness function was defined as the sum of squared errors in a number of measurement points belonging to the major loop. The number of data points used (801) was redundant compared to the problem dimension (5) in order to diminish the possible influence of measurement errors.
Figure 3 presents the evolution of fitness value during estimation. The final fitness value after 40 iterations was 1,15 x 10^{12} [$(A/m)^2$].

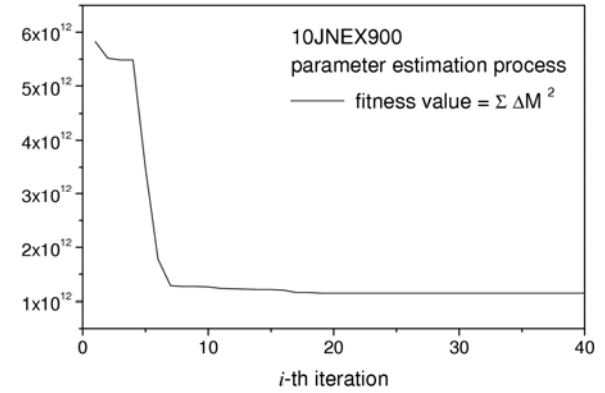

Fig.3. The evolution of fitness value during estimation of model parameters for 6,5 % wt. Si NO steel sheet

The measurements were carried out using Single Sheet Tester on a computer-aided laboratory stand, which fulfilled all the requirements of IEC 60404-3 [20,21].

Minor loops in quasi-static conditions
It was found, that modelling of minor loops with the same values of model parameters as for the major loop resulted in discrepancies between the modelled and the measured loops. Therefore it was assumed, that the model parameters a and k referred to their major loop values could be expressed as the functions of relative magnetization level. The values of scaling coefficients were found using the "branch-and-bound" algorithm and log-log fitting of the expected functional dependencies for those values of B excitation, where the domain wall movement was expected to dominate, cf. Fig. 2.
In order to demonstrate the validity of the proposed approach in Figs. 6-7 exemplary modelling results are depicted. The values of the parameters were updated according to $a_{minor} = \exp(0,2) \times a_{major} \times (B_{minor} / 1,3)^{(-0,9)}$ [A/m] and $k_{minor} = \exp(-0,02) \times k_{major} \times (B_{minor} / 1,3)^{0,75}$ [A/m].
For comparison in Figure 6 a minor loop obtained for the uncorrected set of model parameters is shown.

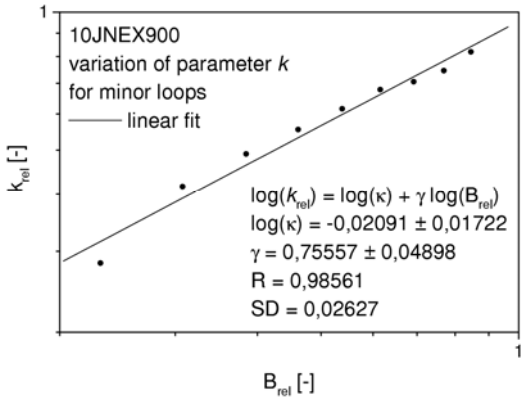

Fig.4. Variation of parameter k for minor loops

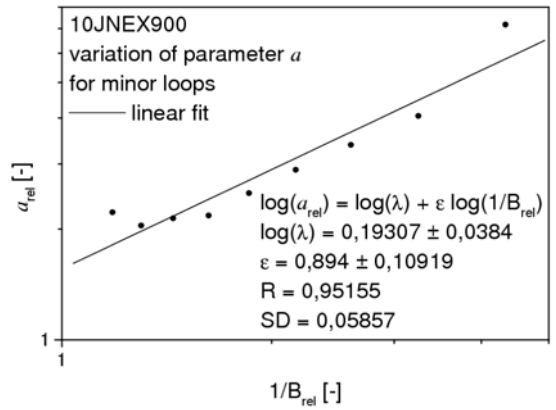

Fig.5. Variation of parameter a for minor loops

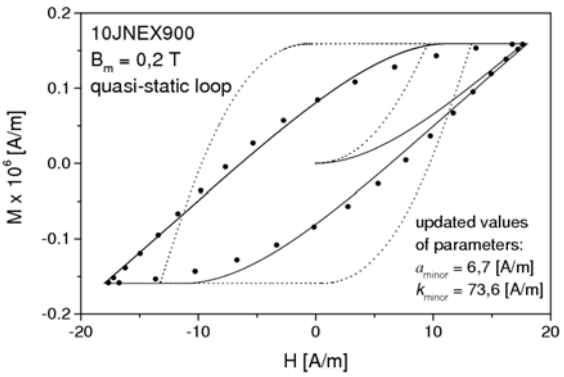

Fig.6. Exemplary modeling results: dots – measurement points, solid line – modelled loop with updated parameters, dotted line – modelled loop with the same parameters as for the major loop

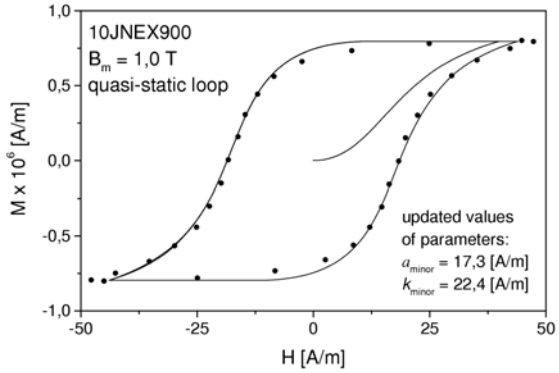

Fig.7. Exemplary modeling results: dots – measurement points, solid line – modelled loop with updated parameters

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Conclusions

In the paper an approach allowing for an accurate modelling minor hysteresis loops under quasi-static conditions was presented. For the description of hysteresis phenomenon a model combining Jiles-Atherton approach and product Preisach model was used. The modelling strategy consisted in making two of model parameters dependent on relative magnetization level. The modelling results were compared to experimental data for the state-of-the-art core material – microcrystalline high silicon steel. It can be stated that satisfactory agreement between the measured and the modelled symmetric hysteresis loops was obtained.

Future work shall focus on coupling the developed model with a behavioural description of rate-dependent dynamic effects [22] within the FE framework to predict the dynamic behaviour of magnetic materials under increased excitation frequency.

Acknowledgement

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