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COMPLEX MAGNETIC CHARACTERISATION OF IRON-SILICON TRANSFORMER SHEETS

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Different transformer lamination alloys were studied by non-destructive magnetic methods in the present work. Nine different commercial grades were compared. The investigated alloys were strongly different quality products but all of them were so-called electro-technical steels produced for laminated iron core production. Seven of them were non-oriented and two of them were grain-oriented with cube texture. All of them contain silicon alloying to improve their magnetic properties.

In this study the so called hyperbolic model of magnetization was applied for the experimental magnetization curves. It was proved that the applied model is excellent for describing mathematically the experimental magnetization curves. However, the application of the model is useful for evaluating the measured data as well. The model assisted data evaluation can provide not only the classical magnetic parameters but new information like the ratio of irreversible and reversible components of magnetization as well. Therefore, it can help the better understanding of the connection between the magnetic parameters and their microstructural background and can extend the application possibilities of magnetic measurements.

Keywords: T(x) model, minor loops, magnetisation curve, irreversible magnetization, power loss

1 INTRODUCTION

Iron-silicon alloys are traditionally used for producing laminated iron cores for transformers used in 50-60 Hz frequency. In this work nine different so-called electro-technical steels [1] were set as test samples. They were chosen intentionally to have strongly different magnetic properties. Among them there are top, medium and definitely poor quality products as well. Their minor, saturation magnetic hysteresis loops and the normal magnetization curves were measured by alternating current measurement.

The modified form of the so called T(x) model of magnetization was applied for the measured experimental magnetization curves. The aims of this were testing the applicability of the modified model and obtain new non-classical magnetic parameters for material characterization.

2 THEORETICAL PART

The T(x) or hyperbolic model of magnetization was introduced by Takacs [2, 3]. This model presents a closed form mathematical description of magnetic hysteresis loops and normal magnetization curves based on physical principles, rather than simply on the mathematical curve-fitting of observed data. This model can be applied for a lot of magnetic materials using only some fitting parameters. One of the most important advantages of the hyperbolic model is that each used parameters have direct physical meaning. It can help understand the physical sub processes of the magnetization.

The T(x) model supposes that the magnetization process has an irreversible and a reversible component. The decomposition of the magnetization process to irreversible and reversible components is generally accepted in the literature [4, 5]. The form of the originally introduced T(x) function is a combination of a hyperbolic and a linear function [2, 3] where these parts represent the reversible and the irreversible part of magnetization, respectively (1).

$$T(x) = A_0 x + B_0 \tanh C_0 x \qquad (1)$$

where: x is the normalized magnetic field strength. A_0, B_0 and C_0 are fitting parameters of the model.

During the application of that form of the model for soft magnetic and structural materials it was found that the linear function is not appropriate for describing the reversible magnetization process. Therefore, the T(x) function was modified and a hyperbolic tangent function was introduced for describing the reversible magnetization effect (2). This $T^*(x)$ function is better in physical point of view also because it is able to describe the saturation phenomenon in the high field region.

$$T^*(x) = \frac{\tanh(N_i x) + \phi \tanh(N_r x)}{1+\phi} \qquad (2)$$

where Ni and Nr are the scaling parameters for irreversible and reversible magnetization, respectively. Φ is a fitting parameter.

Following the way of Takacs's calculation [3] the whole hysteresis loop can be constructed. According to that, the T*(x) function shifted horizontally by α as well as vertically by β in symmetrical way. The ascending and descending arms of the hysteresis loop are (3):

$$Y_+(x) = \frac{\tanh[N_i(x-\alpha)] + \beta + \phi \tanh(N_r x)}{1+\phi}$$
$$Y_-(x) = \frac{\tanh[N_i(x+\alpha)] - \beta + \phi \tanh(N_r x)}{1+\phi} \qquad (3)$$

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where Y is value of the normalized magnetic induction, α is the coercivity in the normalized scale.

Taking into consideration that in saturation the ascending and descending part of the hysteresis loop must intercept each other the value of β can be calculated.

The loci of the crossover points of the up-going and down-going parts of the minor loops and the saturation hysteresis loop will be referred as normal magnetization curve in this paper. For the normal magnetization curve the following mathematical function can be obtained (4).

$$Y(x) = Y_{irrev} + Y_{rev} = \\ = \frac{\tanh[N_i(x+\alpha)] + \tanh[N_i(x-\alpha)]}{2(1+\phi)} + \frac{\phi \tanh(N_r x)}{(1+\phi)} \qquad (4)$$

In equation 4 the first part belongs to the irreversible the second is to the reversible magnetization process. From this can be seen that the Φ represents the ratio of the reversible and irreversible magnetization in the saturation range (5).

$$\frac{Y_{rev}}{Y_{irrev}} \rightarrow \phi \quad if: \quad x \rightarrow \infty \qquad (5)$$

3 EXPERIMENTAL ARRANGEMENTS

A specially designed permeameter-type magnetic property analyzer which was developed at the Department of Materials Science and Engineering of BUTE was used for measuring the magnetic hysteresis curves. The applied measuring yoke contains a robust "U" shaped laminated Fe-Si iron core with a magnetizing coil. The excitation current was sinusoidal (5 Hz) produced by a digital function generator and a special power amplifier used in voltage regulated current generator mode. The pick-up coil was around the middle of the specimen. The permeameter completely controlled by a personal computer in which a 16 bit National Instruments input-output data acquisition card accomplished the measurements. The applied maximal excitation field strength was 15 A/cm. In each case 400 minor hysteresis loops and the saturation loop were measured.

Each hysteresis loops were recorded by measuring 1000 point pairs of them. The excitation magnetic field was increased in steps and there was 5 seconds delay between the increase of the excitation and the data acquisition for hysteresis loops to ensure the sample's perfect magnetic accommodation. All the magnetic measurements were completed by using 5 Hz sinusoidal excitation frequency. Because of the relatively low excitation frequency and small thickness of the samples (0.35 mm) the completed magnetic measurements can be considered as pseudo-static and it can be supposed that the effect of eddy-currents to the magnetisation curves was not significant.

The permeameter allowed us to derive all the traditional magnetic properties from the hysteresis loop like saturation induction, remanent induction, coercivity, relative permeability and hysteresis loss values.

4 TESTED SAMPLES

The measured samples were so called electro-technical steels which were different products with strongly different magnetic properties. Samples E5A and E5B were grain-oriented with cube texture the others were non-oriented. As an illustration the measured hysteresis loops of three of the investigated samples are displayed in Fig.1.

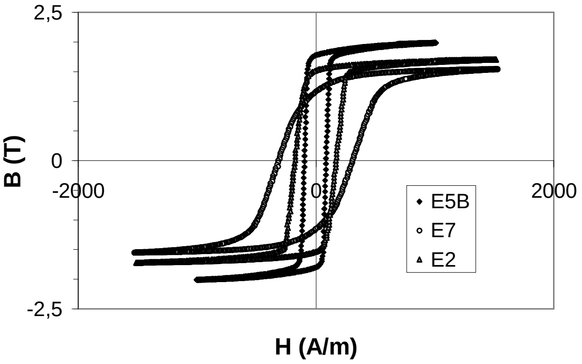

Fig. 1. Hysteresis loops of some tested samples.

This set of specimens was used as model materials for testing the usability of the proposed model. From the iron-silicon metal sheets 150*30 mm specimens were cut. The thickness of each samples were 0.35 mm. They were longitudinally magnetized according to their rolling direction.

The relative initial (μ_0), maximal permeability (μ_{max}) and the saturation induction (B_{max}) values were determined from the measured magnetization curves. These results are summarised in Tab.1.

Table1. Saturation induction and permeability values of the tested samples.

Sample	B_{max} (T)	μ_0 (-)	μ_{max} (-)
E1	1.71	2730	9303
E2	1.88	3942	10117
E3	1.46	2297	9568
E4	1.89	9264	16330
E5A	1.91	12351	22024
E5B	2.03	13239	23231
E6	1.86	583	4546
E7	2.13	450	2834
E8	2.11	400	2596

The tested samples were sorted in increasing order of their maximal differential permeability values (Fig.2). It this point of view the sample E8 can be considered as the worst and the samples E5A and E5B as the best quality electrical steel alloys in the given set.

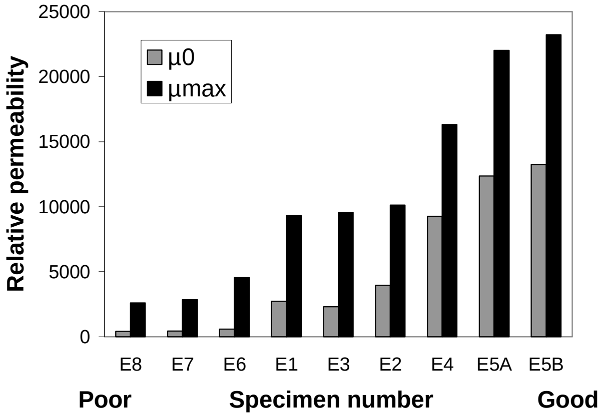

Fig. 2. Samples sorted in increasing order of the maximal permeability.

5 RESULTS AND DISCUSSION

The theoretical normal magnetization curve derived from the modified form of the T(x) model (4) was fitted to the measured normal curves. The experimental normal magnetization curves were generated as the loci of the crossover points of the up-going and down-going parts of the measured minor hysteresis loops. The fitting parameters were determined by applying the Levenberg-Marquardt iteration method. The deterministic coefficient of the fitting was always better than 0.997 therefore, the curve fitting can be considered as good in all cases. The results of curve fitting demonstrated by Fig. 3 and 4.

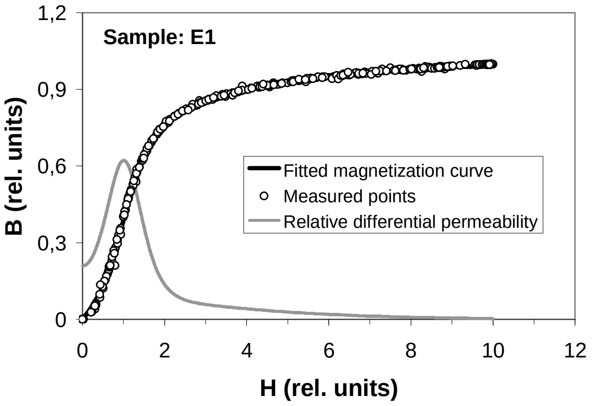

Fig. 3. Measured normal magnetization curve, the fitted magnetization curve and the calculated curve of relative differential permeability of the E1 sample (excellent fitting R^2=0.9993).

Both figures contain the measured points of the normal magnetization curve, the fitted magnetization curve according to Eq.4 and the curve of relative differential permeability which was calculated as the first derivative of the fitted curve.

The fitted normal magnetization curves are practically perfectly fit to the experimental points (R^2 is always better than 0.999) in case of samples E1, E2, E3, E4, E5A, E5B and E6. Acceptable but not as perfect fitting was obtained in the cases of E7 and E8 samples (R^2 = 0.997).

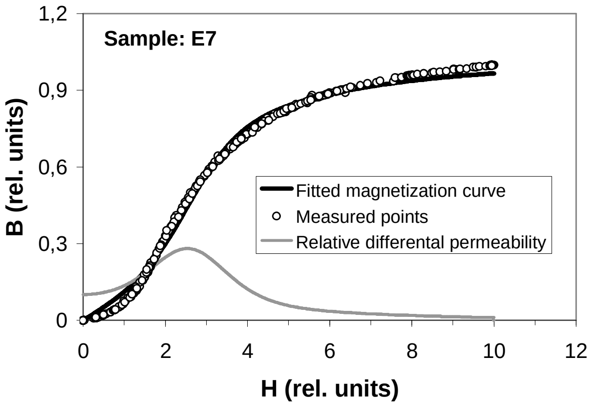

Fig. 4. Measured normal magnetization curve, the fitted magnetization curve and the calculated curve of relative differential permeability of the E7 sample (acceptable fitting R^2=0.997).

The fitted magnetization curves allow us the determination of the irreversible component of the total magnetization process. The irreversible ratio (R_{irrev}) in percent was calculated by Eq.6. It expresses how many percent is the contribution of the irreversible magnetization to the value of magnetic saturation induction.

$$R_{irrev} = \frac{1}{1+\phi}100\% \qquad (6)$$

where $R_{irrev} + R_{rev} = 100\%$. Fig.5 shows the variation of irreversible ratio of magnetization and coercivity of the nine investigated specimens. As it can be seen in case of good quality transformer sheet materials the coercivity values are low and the irreversible ratio of magnetization is large actually close to 100%. In contrast with the poor quality alloys where the large coercivity is associated with relatively low irreversible ratio.

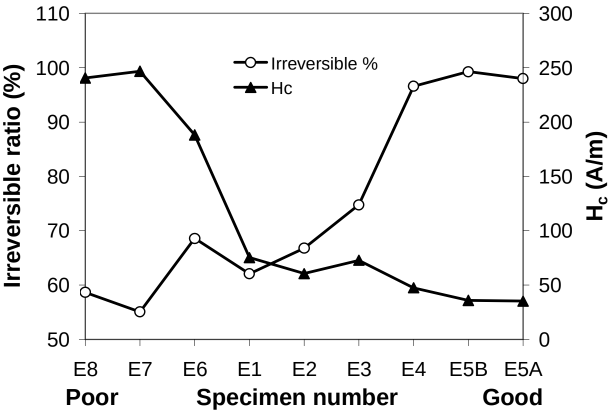

Fig. 5. Variation of irreversible ratio of magnetization and coercivity of the nine investigated specimens.

In other words, in case of good soft magnetic allows the magnetization process is practically only an irreversible process while the relatively poor soft magnetic allows have significant reversible magnetization contribution as well. The highest obtained reversible ratio (R_{rev}) was 45% in case of the E7 sample.

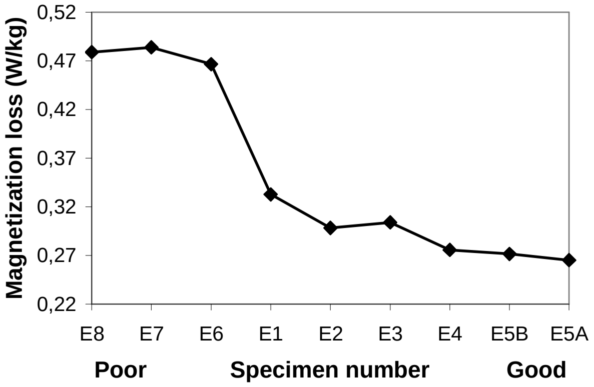

Fig. 6. Variation of magnetization loss of the nine investigated specimens.

Fig.6 demonstrates the variation of the magnetization loss of the nine investigated specimens. The values of this AC magnetization loss were calculated from the saturation hysteresis loop areas measured by 5 Hz sinusoidal excitation. As it can be seen the high power loss is associated with high coercivity and low irreversible ratio as well.

6 CONCLUSION

The kinetics of the magnetization process and the application possibilities of the modified T(x) model for soft magnetic transformer lamination alloys were investigated.

Magnetization curves and macroscopic magnetic properties of nine different Fe-Si transformer sheets were measured. Seven of them were non-oriented and two of them were grain-oriented with cube texture. A modified form of the T(x) model of magnetization was introduced and applied for the measured normal magnetization curves. It was proved that modified form of the T(x) model is excellent for describing the shape of normal magnetization curves in case of good quality electro-technical steels.

It was found that the decrease of coercivity is associated with the increase of the irreversible ratio of the magnetization process and it is associated with the decrease of magnetization loss.

It was demonstrated that the application of the model allows us to determine the ratio of irreversible and reversible components of the total magnetization process which could help in the better understanding the kinetics of the magnetization process and the magnetic properties.

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