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COMMUNICATIONS

Relationships between grain size in self-developed soft magnetic composites and the Grucad hysteresis model

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Soft magnetic composites (SMCs) have been in the spotlight of magnetic community due to their unique properties which can easily be tailored up to a specific application. The present paper is focused on the possibility to develop SMC cores produced from iron powder mixed with suspense polyvinyl chloride. Important processing parameters like grain size are correlated with the parameters of a simple phenomenological hysteresis model developed by the Grucad research group.

K e y w o r d s: soft magnetic composites, grain size, magnetic properties, Grucad model

1 Introduction

Soft magnetic composites (SMCs) have been the subject of intensive research around the world in recent years [1-8]. The engineering community has noticed their benefits *eg* the flexibility in shaping complicated 3D magnetic circuits and the possibility to tailor their magnetic properties by applying appropriate processing conditions and modifying their chemical composition. Most of research on SMCs is carried out on commercially available products like Somalloy from Höganäs [10,11]. In the present paper we focus on the magnetic properties of self-developed SMC cores made of iron powder and suspense polyvinyl chloride pressed together at a relatively low compacting temperature. The effect of grain size of the iron powder on the shape of hysteresis loops is correlated with an appropriate update of GRUCAD model parameters.

2 THEORETICAL PART

Hysteresis curves of SMCs have been described using different formalisms: the Preisach model [10,11], different modifications of the Jiles-Atherton description [10-14], the hyperbolic $T(x)$ model [13, 15] and recently the Schneider proposal [16]. In the present paper we consider the application of Grucad description [17-19]. This phenomenological model has a number of advantages: a simple mathematical formulation, easy numerical implementation, decoupling of effects from irreversible and reversible magnetization phenomena. The reversible (anhysteretic) part is described with two equations

$$H_{\mathrm{an}} = \frac{B}{\mu_0} - M_{\mathrm{s}}(\coth\lambda - \frac{1}{\lambda}), \tag{1}$$

$$\lambda = \frac{1}{a}\left[(1-\alpha)H_{\mathrm{an}} + \alpha\frac{B}{\mu_0}\right]. \tag{2}$$

The dimensionless parameter α plays the role of a weighting coefficient between the flux density B and the reversible field strength H_{an} The parameter a, (A/m) is used for adjusting the level of the value for the auxiliary variable λ in the Langevin function (1). The hysteretic part is given as

$$\frac{\mathrm{d}H_{\mathrm{h}}}{\mathrm{d}B} = \frac{H_{\mathrm{Hs}}(\coth\lambda_{\mathrm{H}} - 1/\lambda_{\mathrm{H}}) + H_{\mathrm{h}})}{\gamma\delta} \tag{3}$$

with λ_{H} defined as

$$\lambda_{\mathrm{H}} = \frac{H_{\mathrm{h}} + \delta H_{\mathrm{HS}}}{a}, \tag{4}$$

where $\delta = \pm 1$ is the sign of $\mathrm{d}B/\mathrm{d}t$ The parameter H_{Hs}, (A/m) is responsible for loop width in quasi-static conditions (it corresponds to much extent to coercive field strength), whereas the parameter γ, (T) is responsible for the loop shape in the knee region. Both field components *ie* and H_{an} H_{h} are summed up together to yield the total field strength applied to the sample.

As it follows from (3), the input variable is magnetic flux density, therefore the considered description belongs to the group of the so-called inverse models, $H = H(B)$. It is thus useful in the direct analysis of measurement data carried out in accordance with the international standard IEC 60404, which assumes preserving a sine B waveform. Moreover it is may be readily implemented in 2D Finite Element codes based on magnetic vector potential $\vec{A}$, ($\vec{B} = \mathrm{rot}\,\vec{A}$), when magnetic flux density in a given element is known ahead of magnetic field intensity.

3 EXPERIMENTAL PART

Cylinder-shaped samples of 99.5% wt pure Fe and 0.5% wt PVC were formed using a hydraulic press with a

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Table 1. Values of model parameters *vs* grain size

Sample	Grain size	a (A/m)	H_{Hs} (A/m)
A	< 50 μm	5900	500
B	50100 μm	5800	480
C	100150 μm	5700	460

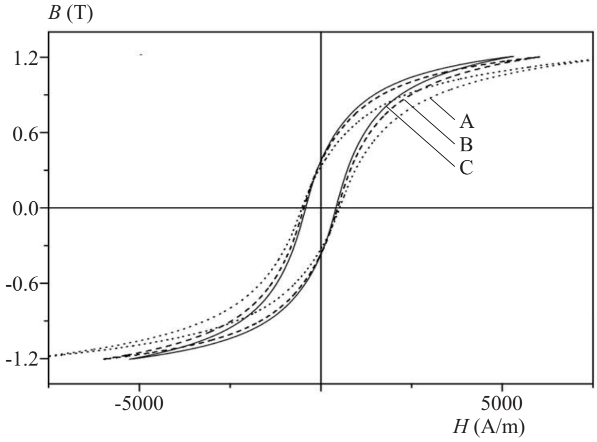

Fig. 1. Major measured hysteresis curves for three SMC samples differing in fe grain size

form and a thermocouple band for controlling heat treatment conditions. The dimensions of the samples were: the outer radius 25 mm, the inner radius 15 mm and height 10 mm. The samples differed in iron grain size. The iron powder was prepared in a shaker with sieves of different mesh size. The grain size for three samples, whose hysteresis loops measured at $B_{\mathrm{m}} = 1.2$ T are shown in Figure 1, were as follows: A less than 50 m, B from the range $\langle 50; 100\rangle$ μm, C from the range $\langle 100; 150\rangle$ μm. The hysteresis curves and power loss densities were measured using a computer-aided REMACOMP C-200 system produced by Magnet-Physik Dr Steingroever GmbH, Kln, Germany. The system uses an oscillographical recording method. The magnetic field strength H is determined directly from the voltage drop on a low inductance shunt resistor. The voltage drop as well as the voltage induced in the secondary winding are simultaneously sampled by two fast 12-bit AC converters.

The voltage induced in secondary winding is numerically integrated in order to obtain instant values of magnetic flux density B and polarization J. The time dependencies of H and B are subsequently used for further processing. The basic measuring principle corresponds to the IEC 60404-6 standard (digital method).

The quasi-static equations were used during modelling, taking into account the internal structure of the examined SMCs. As the non-conductive polyvinyl chloride prevented to much extent the flow of inter-grain eddy currents [20], and the excitation frequency was relatively low ($f = 50\,\mathrm{Hz}$), we decided to neglect the influence of eddy currents on the shape of the hysteresis loop [21-23]. The model parameters were determined from the measured major loops depicted in Fig. 1. The values of three parameters were kept constant for all loops during modelling, $\alpha = 0.0135$ (-), $M_{\mathrm{s}} = 1.2 \times 10^6$ (A/m), $\gamma = 0.1$ (T). In order to take into account the grain size on the shape of hysteresis loops, we have varied the values of parameters a and H_{Hs}. They are listed in Table 1.

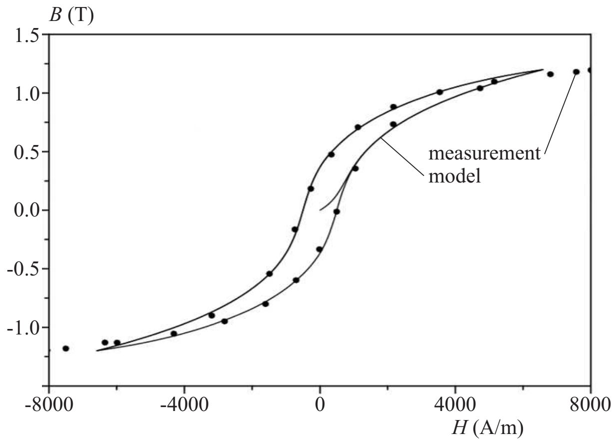

Fig. 2. Measured and modelled hysteresis curves, sample a

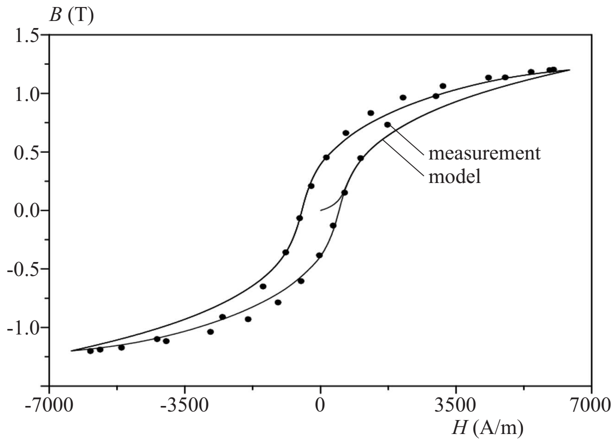

Fig. 3. Measured and modelled hysteresis curves, sample b

Figures 2-4 depict the measured and the modelled hysteresis loops. It can be stated that the Grucad description is useful for modelling the major loops. There are slight discrepancies in the area above loop knee, but

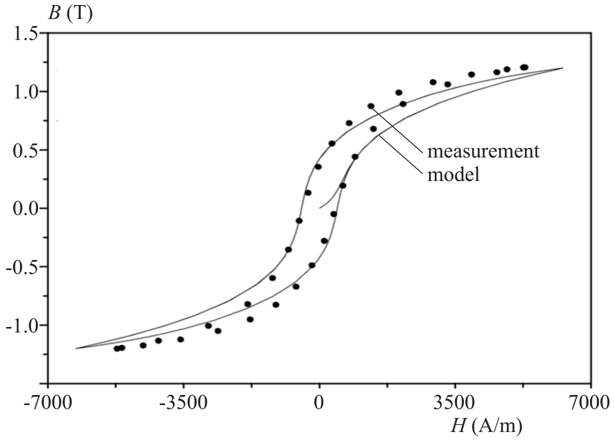

Fig. 4. Measured and modelled hysteresis curves, sample c

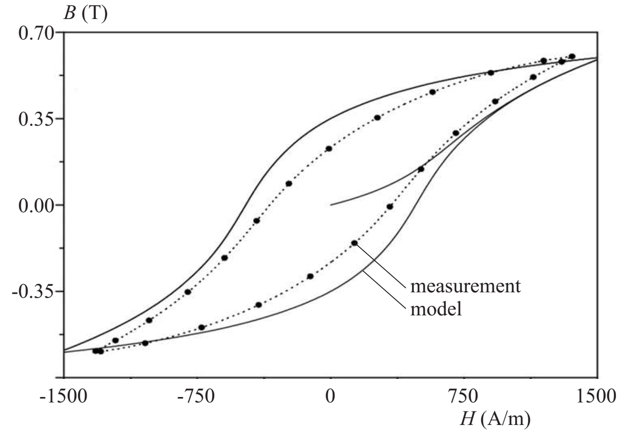

Fig. 5. Measured and modelled minor hysteresis curves, sample B

Table 2. Values of measured and modelled (*) quantities

Sample	H_c (A/m)	$*H_c$ (A/m)	B_r (T)	$*B_r$ (T)	W (kJ/m^3)	$*W$ (kJ/m^3)
A	518.2	499.1	0.327	0.365	112	110.5
B	466.5	479.2	0.367	0.394	102	106.1
C	417.6	459.2	0.373	0.422	93	101.4

generally the shapes are reproduced well. In order to assess the model accuracy qualitatively, we have compared the measured and the modelled values of coercive field strength and remanence flux density. Moreover we have integrated numerically the areas of hysteresis loops (trapezoid method) in order to estimate power loss density. The results are listed in Table 2. It can be stated that the maximum absolute error between the measured and the modelled quantities does not exceed 13.3% in all cases.

It can be observed that the increase of grain size results in lowering power losses in the developed SMC cores. This conclusion is consistent with the results by Shokrollahi and Janghorban [3]. Moreover the initial and maximum measured permeabilities increase upon the increase of Fe grain size, in accordance with the results by Anhalt [4]. Both trends are reproduced qualitatively by the Grucad model.

In order to check whether the considered description is able to cope with minor loops we have carried out modelling for $B_{\mathrm{m}} = 0.6$ T. The same values of model parameters as for the major loop were kept during modelling. Measured and modelled hysteresis loops for the sample B *ie* for grains from the range $\langle 50; 100 \rangle$ μm are shown in Fig. 4. Qualitatively similar loops were obtained for the other samples. It can be stated that the modelled hysteresis loops generally overestimate the values of coercive field strength and remanence flux density. The area of modelled loop is also significantly larger than the one from measurements. The relative absolute errors for the quantities of interest, *ie* H_{c}, B_{r} and W for the case depicted in Figure 4 were equal to 50.6%, 39.7% and 49.9%, respectively.

Despite relatively large values of errors obtained for the minor loops we believe that the model might be useful for the designers of magnetic circuits in electrical machines as a part of CAD routine.

4 Conclusion

Magnetic cores made of 99.5% wt pure Fe and 0.5% wt PVC were formed using a hydraulic press with a form. The grain size of iron powder was chosen as the input variable for optimization of their magnetic properties like the quasi-static coercive field strength. It was found that the best magnetic properties (highest permeability, lowest coercive field strength and power losses) were obtained for the coarse grain size. For the description of quasi-static hysteresis loops the low-dimensional Grucad model was chosen. The model is consistent with thermodynamics of irreversible processes. The major loops were accurately described with the considered description but for the minor loops only a qualitative agreement with experiment was met. Two of model parameters were varied in dependence on the grain size. One of the parameters was responsible for the shape of the anhysteretic curve, the other was related to the width of quasi-static loop. It was found that the parameter a decreases upon the increase of grain size, contrary to the parameter H_{Hs} .

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