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Prediction of anisotropic properties of grain-oriented steels based on magnetic measurements

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Magnetic properties of grain-oriented steels are inseparably linked to their anisotropy. A proper characterization of anisotropy is thus crucial for practical applications. In the paper a description based on magnetic measurements carried out for three well-defined cutting angles is presented. It is shown that it is possible to predict magnetic properties of interest (coercive field strength, remanence flux density) for an arbitrary angle using a limited number of measurements.

Keywords: anisotropy, magnetic properties, grain-oriented steel

1 Introduction

Grain-oriented (GO) steels are in the second place (after non-oriented alternator steels) on the market of soft magnetic materials (SMMs), as far as their annual production volume is concerned. Their share in the SMM market is around 16% (about 1.7 million tonnes) [1]. The main factor contributing to the development of this branch of metallurgical industry is the growing demand for electrical energy in developing, highly populated countries, what implies the need to develop the existing grid infrastructure and to install new transformer units, which use GO steel as core material for their magnetic circuits. According to the estimates of International Energy Agency the global capabilities to produce electric energy is likely to increase by 3% *ie* around 150 GW in 2030. This justifies the interest of the scientific community in the examination of GO steels aimed at the continuous improvement of their properties.

2 THEORETICAL PART

Magnetic properties of GO steels are significantly affected by their microstructure, texture and anisotropy [2-8], *cf* also Fig. 1. This fact implies the necessity to develop new design methods for magnetic circuits in electrical machines. In order to limit the number of tedious measurements to a necessary minimum, it is desirable to focus on the descriptions that make it possible to predict the shapes of $M - H$ dependencies for arbitrary angles.

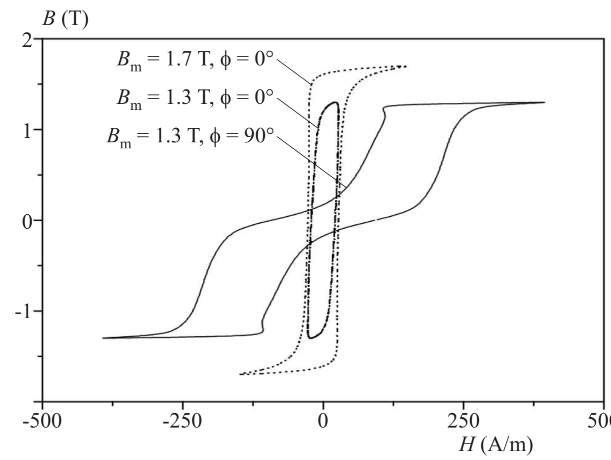

Fig. 1. Typical hysteresis curves measured for a GO steel

It should be remarked that the steel producers rarely provide catalogue information on $M - H$ dependencies for angles different from the rolling direction. Most often the $M - H$ curves are either provided for the angle $\phi = 0°$ or for the mixed $(0° + 90°)$ samples. However, it is well known that the worst magnetic properties for iron-based alloys are expected for the angles $\phi = 54° - 60°$. The present paper is focused on the possibility of predicting magnetic properties of GO steel such as remanence flux density and coercive field strength for arbitrary angles using a simple description based on magnetic measurements carried out for three angles $\phi = 0°,\ 45°,\ 90°$. A concept of prediction of magnetic properties of GO steels for an arbitrary direction using an appropriately chosen combination of samples cut for the above-mentioned angles was suggested by Penin Santos et al. in 2006 [9]. De Campos provided theoretical foundations for the approach in [10]. Quite recently the method was scrutinized by Chwastek et al. [11]. The paper [11] was focused on model verification for normal magnetization curves and power losses,

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whereas the present contribution is devoted to description of well-defined points on the hysteresis curves, namely the remanence flux density and the coercive field intensity.

According to the theory resulting from Bunge's analysis of Orientation Distribution Functions (ODFs) [12], angular variation of any magnetic property can be described using three first ODF coefficients

$$A = A_0 + A_1 \cos 2\phi + A_2 \cos 4\phi \qquad (1)$$

where the values of parameters A_{i} are related to the values from measurements for the angles $\phi = 0°,\ 45°,\ 90°$

$$A_0 = 0.25\left[A\left(0°\right) + A\left(90°\right) + 2A\left(45°\right)\right] \qquad (2)$$

$$A_1 = 0.5\left[A\left(0°\right) - A\left(90°\right)\right] \qquad (3)$$

$$A_2 = 0.25\left[A\left(0°\right) + A\left(90°\right) - 2A\left(45°\right)\right] \qquad (4)$$

3 EXPERIMENTAL PART

Samples of conventional GO 3%Si-Fe steel, 0.27 mm thick (grade M4) were laser cut in the form of single strips 30 × 305 mm at every 10 degrees from 0 to 170 degrees. Their hysteresis curves were measured under controlled sinusoidal flux density waveform at mains frequency $f = 50$ Hz in an air-compensated single strip tester. The reproducibility of the results was within 0.3% as compared to a system traceable to the NPL equipment (national UK Standard) [13].

Figure 2 depicts a sketch of the arrangement of single strip sample. Air compensation coils are not shown for clarity. As pointed out by Tumaski and Baranowski [14] Single Strip Testers are not standardised and thus less common in magnetic measurements than Epstein frames or Single Sheet Testers. Yet their use has some serious advantages, for example it is possible to test the non-uniformity of material using localized measurements.

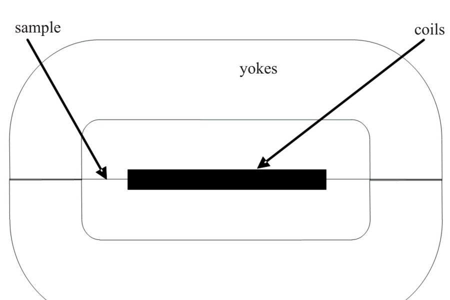

Fig. 2. Arrangement of the single strip tester used for experiments in this paper

Figure 3 depicts a comparison of measured and modelled values of coercive field strength for the highest value of peak flux density, B_m=1.3 T, which could be achieved for all directions. From Fig. 3 it is evident that the considered method allows one for an excellent reproduction of the measured $H_c = H_c(\phi)$ trend. This is consistent with the results of previous research concerning the usefulness of the method to describe the angular variation of power losses. Assuming in the first approximation that coercive field strength is directly proportional to power losses, one expects a similar dependence both for H_c and P_{total} *vs* cutting angle ϕ. The maximum value of the absolute error for the coercive field strength was obtained for the angle $\phi = 10$ deg was 16.6%. The average absolute values of the error were significantly lower, namely 4.3%.

Figure 4 depicts an analogous comparison for the measured and modelled values of remanence flux density. The accuracy of representation was significantly lower in this case. The highest value of the error was obtained for $\phi = 70$ deg, its absolute value was 37.9%, whereas the average absolute value of error was 13.2%.

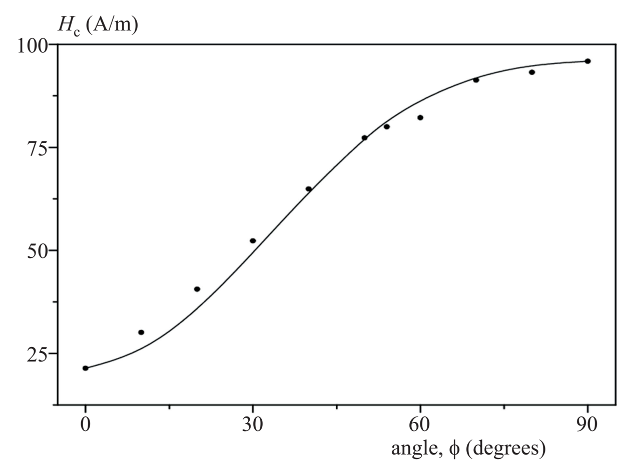

Fig. 3. Model verification for the coercive field strength using the major loop ($B_{\mathrm{m}} = 1.3$ T), dots denote the values from measurements, whereas line represents the predicted values.

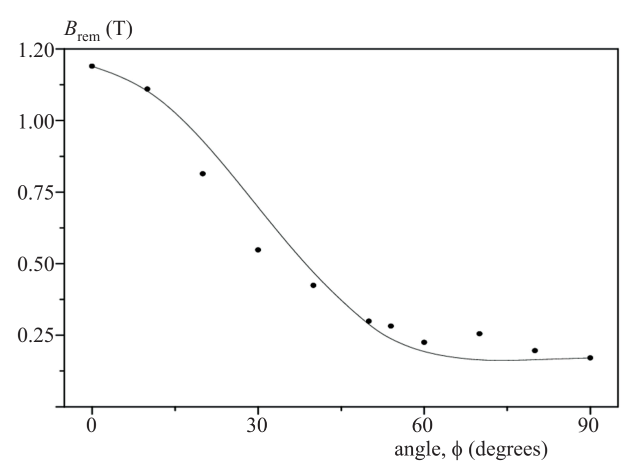

Fig. 4. Model verification for the remanence flux density using the major loop ($B_{\mathrm{m}} = 1.3$ T). Dots denote the values from measurements, whereas line represents the predicted values.

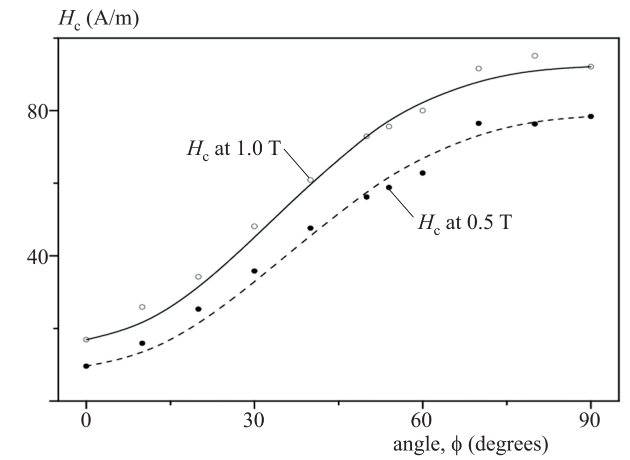

Fig. 5. Model verification for the coercive field strength using the minor loops.dots denote the values from measurements, whereas lines represent the predicted values

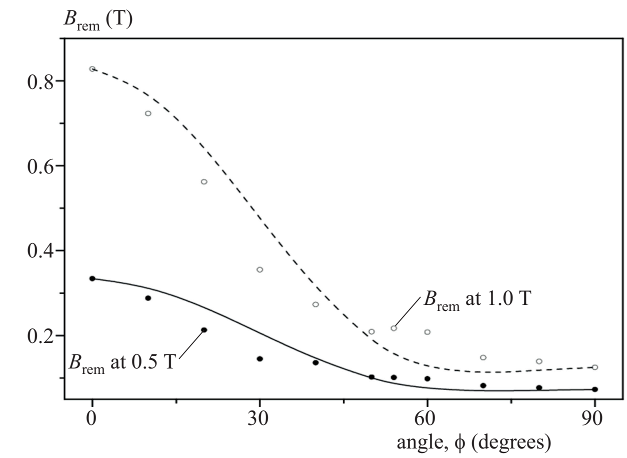

Fig. 6. Model verification for the remanence flux density using the minor loops.dots denote the values from measurements, whereas lines represent the predicted values

In Fig. 5 and Fig. 6 the model verification is shown for lower values of excitation induction. It can be stated that the considered method, based on measurements for three cutting angles $\phi = 0°$, $45°$, $90°$, is capable of reproducing qualitatively the observed $H_c = H_c(\phi)$ and $B_{rem} = B_{rem}(\phi)$ trends. The maximum values of absolute error for the coercive field strength were obtained for $\phi = 10$ deg. They were below 21% both for $B_m = 0.5$ T and 1.0 T. The average absolute errors were significantly lower: 4.7% for $B_m = 1.0$ T and 6.4% for $B_m = 0.5$ T.

The maximum values of absolute error for the remanence flux density were obtained for $\phi = 60$ deg, $B_m = 1.0$ T and $\phi = 30$ deg, $B_m = 0.5$ T. They were equal to 40.3% and 41.6%, respectively. The average absolute errors were below 17.3% in both cases.

A general conclusion from the analysis of the presented results is that the presented model is capable of predicting the angular dependencies of coercive fields strength in grain-oriented steels with an accuracy acceptable for engineering calculations. The model predictions for remanence flux density are less accurate. Yet the trend for $B_{rem} = B_{rem}(\phi)$ is well reproduced qualitatively.

4 DISCUSSION

Anisotropic properties of grain-oriented steels are sometimes examined using the Barkhausen method [15, 16]. On the other hand both methods i.e. the one based on measurements of hysteresis loops and the one based on Barkhausen noise measurements might be correlated, as pointed out by Stupakov *et al* [17]. The importance of the present paper relies on the fact that hysteresis loop measurements are simpler to be carried out and require less post-processing in comparison to Barkhausen noise measurements.

The present paper indicates that important loop parameters like coercive field strength and remanence flux density for an arbitrary angle may be predicted using a simple model based on ODF theory. The encouraging modeling results indicate that the considered relationships (1)-(4) might be introduced into some advanced hysteresis models like the description advanced by Jiles and Atherton [18]. Thus future work shall focus on a comparison of the approach relying on the introduction of relationships (1)-(4) into the macroscopic hysteresis model with the existing phenomenological extensions [19-22].

5 CONCLUSION

In the paper a description of anisotropic magnetic properties based on Bunge's ODF theory has been presented. The model has been verified using measurement data for a 0.27 mm thick 3.2% SiFe GO steel sample concerning coercive field strengths and remanence flux density for different excitation levels at mains frequency. The model might be useful for the designers of magnetic circuits in electrical machines as a part of CAD routine.

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