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MEASUREMENT OF NON-ORIENTED STEELS WITH FIELD CONTROL

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Six different grades of industrial non-oriented steels were measured by a standard single sheet tester and by its modified version with a gap in the middle of the magnetizing coil. A vertical array of three Hall sensors was placed inside this gap to measure the sample tangential surface field profile. The sample sub-surface field was determined by a linear extrapolation of this measured field profile to the sample face. The present work demonstrated that the method of direct field determination expectedly provides more stable and repeatable results with respect to the magnetizing conditions, which gives new opportunities for practical application of the magnetic testing methods. The direct field data also showed excellent correlation with the standard single sheet tester values. This work presented the first results of the on-going project: as the first step, the measurements were done with the maximum induction amplitude of 1.25 T without the sine-wave induction control.

Keywords: direct field measurement, magnetic hysteresis, single sheet tester

1 INTRODUCTION

There are two standard methods for the measurement of electrical steel sheets, which are usually used for hysteresis loss testing at power line frequencies of 50 Hz. The first technique is a classical Epstein apparatus, which due to its high accuracy has remained the main instrument for the evaluation of electrical steel quality in industry for more than a century [1]. The second standard method for measuring the transformer steel sheets is a double-yoke single sheet tester (SST) [2].

Cumbersome constructions of both standard instruments are required for high repeatability of the results, namely for precise evaluation of the sample magnetic field using the magnetization current. However, even for these two standard techniques, there is a small discrepancy in the field determination, which leads to absence of an exact correlation between the data [3, 4].

The objective of the presented work was to introduce the principles of direct field control in practice of magnetic measurements [5]. The set of non-oriented steels was measured in modified SST configuration with Hall sensor array for direct field determination. The direct field results demonstrated good stability and linear correlation with the classical SST data even in the case of open magnetic circuit without the closing yokes.

2 EXPERIMENTS

Six different grades of industrial non-oriented steels were tested in this work [5]. Two strips of each steel of standard sizes 300 × 30 × 0.2-0.5 mm were measured parallel to the rolling directions in three different setup configurations. The corresponding setup schemes are presented in Fig.1. Setup A is a SST analogue needed for comparison of our direct field data with the standard reference. Setup B is its modified version with a gap in the middle of the magnetizing coil. A vertical array of three Hall sensors was placed inside this gap to measure the sample tangential surface field profile. Temperature-stable and 5 mV/G sensitive chips A1321ELHLT-T from Allegro MicroSystems Inc were used. A recently introduced “shielding” approach was used for substantial suppression of the profile gradient: two soft magnetic sheets from laminated FeSi steel force the magnetic leakage flux to flow through the sample (see Fig.1) [6]. The sample sub-surface field was determined by a linear extrapolation of this measured field profile to the sample face [5]. Setup C presents the same Helmholtz type solenoid without the closing yokes (fully open magnetic circuit). The drawback of the two latter setups is slightly inhomogeneous distribution of the magnetization along the tested strip increasing with the induction amplitude level. This is illustrated in Fig.2 by 2-D finite element calculations, which qualitatively explain a deviation of our results at high induction amplitudes.

The measurements were performed with standard 50 Hz sinusoidal driving voltage, which with good accuracy (correlation coefficient r > 0.999) corresponds to 50 Hz sinusoidal magnetic flux for all types of the setup used. The levels of magnetic induction amplitude B_{max} were fixed to 1 and 1.25 T with 0.5% accuracy. At this stage, the investigation was limited to the maximum amplitude of 1.25 T. Higher amplitudes need high magnetizing current and lead to very inhomogeneous strip magnetization for the setups B and C (see Fig.2). They would also need a sine-wave induction control because for the higher amplitudes the correlation coefficient is expected to decrease considerably.

Direct field measurements with B_{max} = 1 T were repeated from two sample sides for each strip to check stability of the field extrapolation approach (the Hall array and the shielding sheets were positioned at opposite sample sides) [5]. To smooth the noisy output of Hall sensors, the final hysteresis loop was averaged over 3000 identical cycles. The SST measurements were done with 300 cycle averaging.

All classical hysteresis parameters (coercivity H_c, hysteresis loss W, and remanent induction B_r) were evalu-

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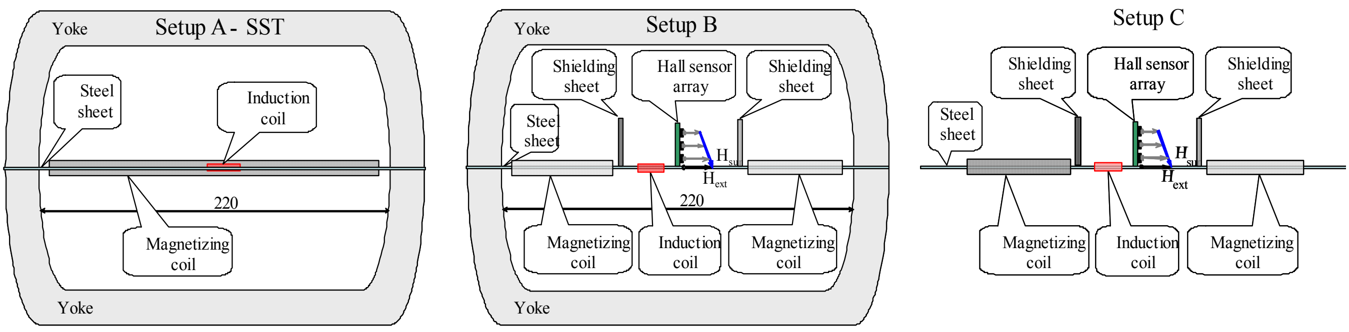

Fig. 1. Schemes of the used measurement setups

ated against three differently evaluated fields: the current field H_i, conventionally evaluated to be proportional to the magnetization current, $H_i = NI/l$, where N is number of turns of magnetization coil carrying current I, $l = 220$ mm is a magnetic path of the circuit (inner distance between the yoke poles); to the surface field H_{sur}, measured by the closest Hall sensor at 1.5 mm distance above the sample; and to the field H_{ext}, linearly extrapolated to the strip surface using the three-point readings of the Hall sensor array

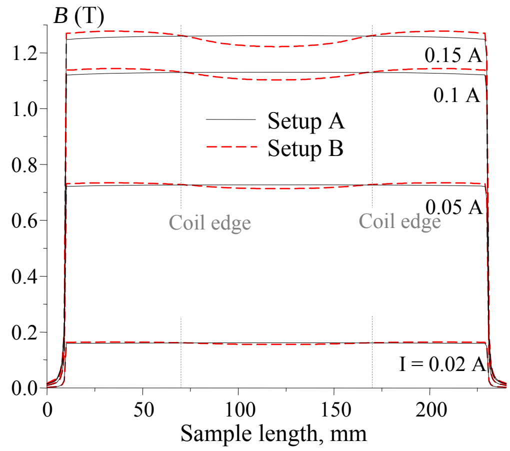

Fig. 2. Distribution of magnetic induction along the sample with the different magnetization setups used

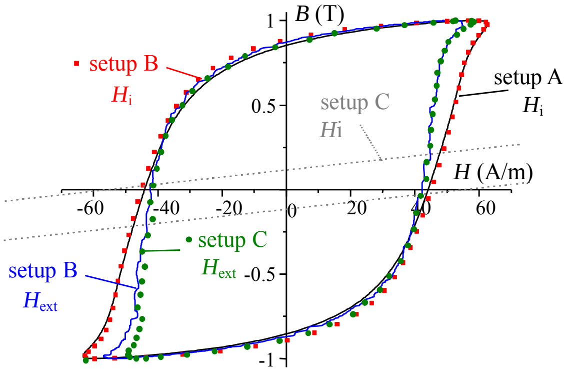

Fig. 3. Typical hysteresis loops of 1 T amplitude, measured by the different setups with the different methods of field determination

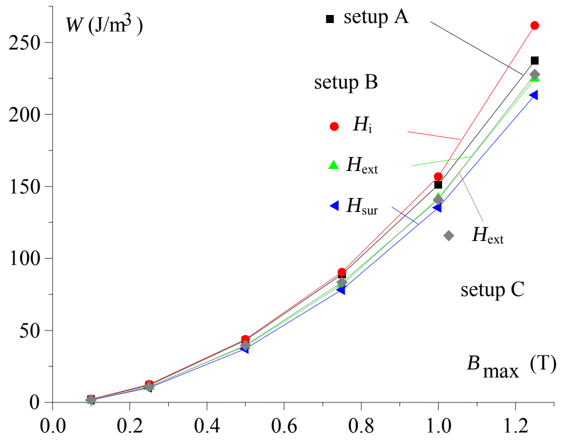

Fig. 4. Dependencies of hysteresis loss for the same sample on the applied induction amplitude

3 RESULTS

Figure 3 presents typical hysteresis loops, measured by the different setups with the different methods of field determination. Setup B provides reasonable and comparable results even with the current field approach. However, these loops are slightly broader than the standard SST loops due to the mentioned inhomogeneous magnetization of the setup B, see Fig. 2. The corresponding direct field loops are already appreciably narrower than the SST loops. The open setup C can not assure reasonable current field data because of huge demagnetization effect. However, the extrapolated field data are practically identical to that of the closed setup B. This is considered to be the main result of this research.

This trend is also illustrated in Fig.4, which presents the dependencies of hysteresis loss for the same sample on the applied induction amplitude. With B_{max} increase, the deviation of the setup B/C data from the standard SST ones becomes larger. The H_{ext} results, obtained with the setups B and C, are identical. The same is valid for the H_{sur} data with more understated values of magnetic field.

Figures.5-7 show the correlations of the classical magnetic parameters (hysteresis loss W, coercive field H_c, and remanent induction B_r), obtained with the different field approaches at the different setups with the fixed B_{max}= 1 T, with the corresponding standard values, obtained with the SST setup A. Excellent and stable linear correlations with the practically unit slope are obtained for the most important hysteresis parameters as the loss and the coercivity. These figures additionally prove the independence of the direct field results on the measurement method (the H_{ext} data are identical for the setups B and C). Unfortunately, the correlations for the remanence are much worse.

The error bars of Fig. 5 to Fig. 7 were evaluated as a standard error of two identical tests from the opposite sample sides. As it was combined with the measurements of 12 different strips, it is believed to prove stability of the introduced method of direct field determination. Data for the two strips of the same grade were presented separately because their difference of magnetic properties can be comparable with that between the different grades. The lines present the best linear fits of the experimental data. The slope, the offset, the Pearson correlation coefficient R and the standard deviation SD of the linear fits are given in the graph labels.

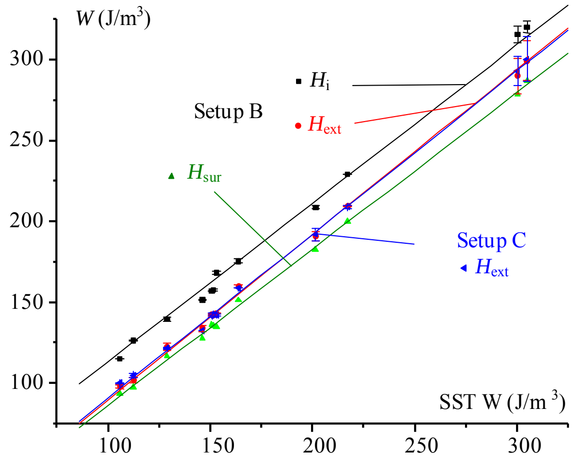

Fig. 5. Correlations of the hysteresis loss W, obtained with the different field approaches at the different setups, with the standard SST data, Setup B: ■ $y = 15 + 0.98x$, R= 0.998; σ_D= 33.4, ● $y = -12.65 + 1.0225x$, R = 0.9993, σ_D= 1.95; ▲ $y = -10.88 + 0.9685x$, R= 0.9995, σ_D = 2.22, Setup C: ◄ $y = -10.25 + 1.0109x$ R= 0.9993, σ_D= 2.62.

4 DISSCUSSION

Measurement with the direct field control is physically more correct than the standard SST technique, which uses the simplest current field approach. It expectedly provides stable and reliable results even for the fully open magnetic circuit, which gives new opportunities for practical application of the on-line magnetic testing methods [5,7,8].

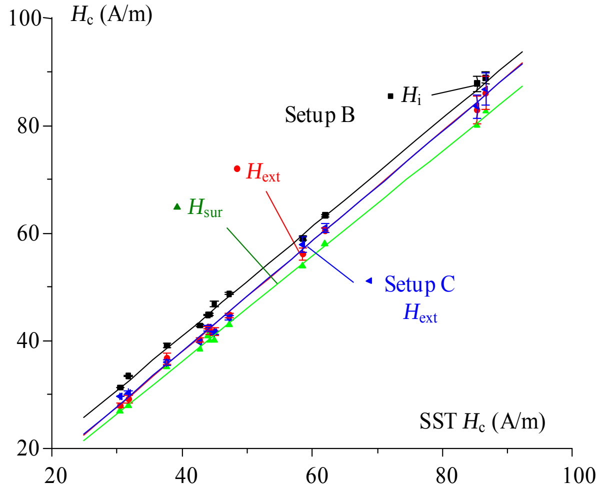

Fig. 6. Correlations of the coercive field H_c, obtained with the different field approaches at the different setups, with the standard SST data, Setup B: ■ $y = 0.47 + 1.01x$, R= 0.998; σ_D= 6.23, ● $y = -3.17 + 1.027x$, R= 0.9977, σ_D= 1.45; ▲ $y = -3.016 + 0.979x$, R= 0.9994, σ_D = 0.67, Setup C: ◄ $y = -2.89 + 1.0228x$ R= 0.9987, σ_D= 1.

However, there are several technical problems in the way of practical applications. The main task is a precise measurement of low magnetic fields. The classical sensors are a standard H-coil [2-4] and a Rogowski-Chattock potentiometer [4,7,8]. Their well-known drawbacks are (i) complexity of preparation and calibration; (ii) large size leading to the requirement of field homogeneity in the large region of the sensor length; (iii) necessity of accurate integration of weak induced voltage (ac measurement only). The modern Hall/AMR sensors have

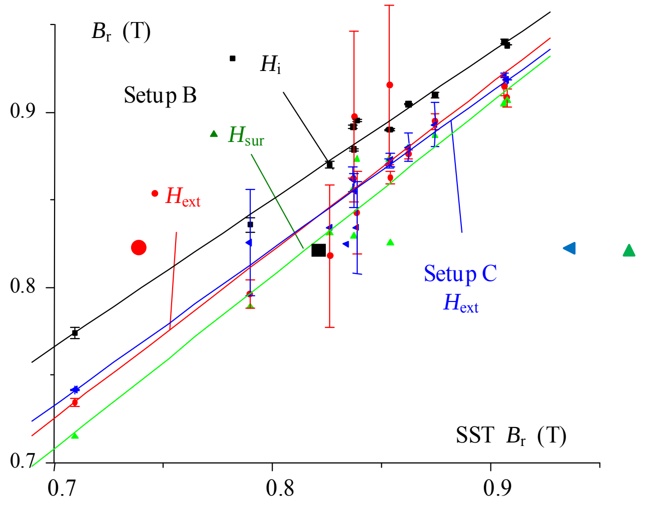

Fig. 7. Correlations of the remanent induction B_r, obtained with the different field approaches at the different setups, with the standard SST data, Setup B: $y = 0.179+0.8394x$, R=0.991; $\sigma_D=6.3\times10^{-3}$ $y = 0.0585 + 0.953x$, R = 0.918, $\sigma_D = 2.3\times10^{-3}$; $y = -0.017 + 0.987x$, R= 0.955, σ_D= 1.7×10^{-3}, Setup C: $y = -0.108 + 0.893x$ R= 0.983, σ_D= 9.4×10^{-3}.

already a sufficient sensitivity. They are also small; their output voltage is simply proportional to the field and independent of the magnetization frequency. However, they are noisier and can be more sensitive to the environmental conditions. In this work the Hall elements were used because they are more suitable for the integration into the sensor array. It was enough to prove our general idea that the direct field measurements can provide new performance capabilities. Selection of the most suitable field sensor for a certain measurement system is a topic of additional serious research.

Thermal noise of the used Hall sensors can not be simply filtered out and should be suppressed by the cycling averaging, which extends the testing time. Moreover, the industrial environment can increase the level of background noise by several times. The Earth magnetic field of comparable value can also influence the results. Despite the zeroing of Hall sensor outputs in a magnetically shielded chamber, small mistake can be introduced by a time deviation of the Earth field. The next problem is the skin effect – the extrapolated sub-surface field can be slightly higher than in the middle of the sample.

The main results of this work are: (i) independence of the extrapolated field data on the measurement approach, see Fig. 3 and Fig. 4, (ii) their excellent linear correlation with the standard SST values for such important hysteresis parameters as loss and coercivity, see Figs. 5 and 6.

Despite the practically unit slope of the linear correlations, there are small non-zero offsets of these fits. This is due to the different approaches of field determination leading to the small deviations of the offset and slope values with respect to different tested materials or used measurement setups. The above-mentioned mistakes of zero field measurement along with the narrow range of tested remanent induction (rectangular shaped hysteresis loop with similar saturation and remanence) result in the worse linear correlation with the SST values. At this stage, it can be used only for rough estimation of B_r, however, accurate estimation of the magnetic induction at low magnetic fields is of modern commercial interest [5].

Our further work will be concentrated on the repetition of these measurements with more industrially relevant setups with a digital feedback for control of the sinusoidal waveform of magnetic flux. Similar measurements will be performed on series of grain oriented steels. The search of more suitable sensor for low field measurement will be also continued.

5 CONCLUSIONS

It was experimentally proved on the series of different non-oriented steels that the hysteresis measurements with the direct field determination provide stable results with excellent linear correlation to the standard single sheet tester data. The main advantage of the direct field approach is that it is useful even for the fully open magnetic circuits.

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