Controllable magnetic hysteresis measurement of electrical steels in a single-yoke open configuration

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Abstract

A newly developed measurement system was comprehensively tested for the industrially attractive case of an open magnetic circuit. Series of industrial electrical steels were magnetised by a single yoke through a gap of several millimeters. According to standards, the magnetic induction waveform was adjusted to a 50 Hz sine curve using a digital feedback procedure. The magnetic surface fields above the sample were measured directly by a vertically mounted array of three Hall sensors. The actual magnetic field was determined by a linear extrapolation of the measured field profile to the sample face. It was experimentally shown that control of the induction waveform and simultaneous direct determination of the sample field make the hysteresis loop measurements independent of the yoke-sample gap. In addition, the obtained physically correct data show good linear correlations with the corresponding standard values measured by a single sheet tester. These outcomes are important for revision of the principles of industrial testing and further development of the measurement standards.

Index Terms

Magnetic hysteresis, magnetic field measurement, open magnetic circuit, magnetic variables measurement, silicon steel.

I. INTRODUCTION

Currently, the accurate measurement of magnetic hysteresis parameters in magnetically open circuits is still a challenge. The main problem is the precise determination of the sample field. It is technically difficult to measure the magnetic field directly. Therefore, the magnetising current is routinely used for evaluation of the sample field. To keep this method of field determination (the so-called current field method) valid, the measurements are commonly performed for magnetically closed specimens, e.g. rings or frames. For magnetically open circuits, the current field is usually reduced by a demagnetising field, which is assumed to be proportional to the sample magnetisation. However, the proportionality (demagnetising) factor can be accurately calculated only for the samples of some special geometries such as ellipsoid or long cylindrical rod [1], [2].

Electrical steels, which are used as the cores of transformers, generators, and motors, are practically the sole type of commercially produced materials whose magnetic hysteresis properties are the main technological parameters of importance. There are two international standards used for laboratory measurements of electrical steel sheets. An outdated Epstein frame, which has been used for more than a century, needs a pseudo-closed square arrangement of steel strips. In the 1980s, a simpler single sheet tester (SST) was introduced, which utilises two large attached yokes to close the magnetic flux of the sample. These two standards define the magnetisation condition in accordance with the operational condition of power lines: 50 Hz sinusoidal magnetisation. The magnetically quasi-closed circuits of the two standards maintain the magnetisation waveform to be nearly sinusoidal at sinusoidal magnetisation voltage with low amplitudes. The cumbersome closed constructions of both standard instruments are also needed to keep the current field method valid [2]–[4].

However, industry needs a reliable testing system, which can be applied on the production line for quality control. In such systems, the magnetisation of the moving steel sheet must be performed through a substantial and sometimes varied air gap between the magnet and the sample. For this open configuration,

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the magnetisation current cannot generally provide a reliable base for evaluation of the sample field [5], [6]. Therefore, an approach that is based on a different principal should be proposed for this non-trivial task. At the moment, only a field compensation technique is accepted to be applicable for the measurement in the magnetically open configuration. This method uses an analogue feedback loop to adjust the magnetisation process to the ideal condition of the closed magnetic circuit, when the current field method can be applied [4], [7].

The *physically based* idea to measure the magnetic surface field directly was suggested a century ago [1], but its implementation has been faced with serious technical difficulties, namely due to a high surface field gradient and non-homogeneous sample magnetisation. Two thoroughly examined techniques using flat air-core H-coil/s for the surface field measurement, a 1-D SST modification and a 2-D rotational SST, have not been recommended as the standard methods because of insufficient reproducibility of the results [2], [3], [8], [9]. Lately, we have investigated this old problem from a slightly different standpoint and proposed several technical innovations to improve the accuracy of the direct field method [10], [11]. Recently the direct field approach has been consistently tested for the quality control of the electrical steels. Preliminary dc experiments were performed to check the stability of field measurements [6], then 50 Hz measurements without the induction waveform control were performed to verify the correlation with the standard SST data [12]. Finally, a unique measurement setup with digital feedback control of the induction waveform and simultaneous direct determination of the magnetic field was developed [4].

This work is devoted to the last major stage of the project, namely to the question of applicability of this novel measurement setup for the magnetically open industrial configuration. The single-yoke magnetisation system was chosen for the comprehensive testing because it is the technically easiest but the magnetically least stable configuration, which is generally accepted to be unusable for the accurate magnetic measurements [3]. The asymmetrical construction of the single-yoke system is considered to lead to nonuniform sample magnetisation. However, the definite advantage of a small surface field gradient at the yoke-free sample side is not usually taken into account [13]. We present an experimental verification of our theoretical expectations that the magnetic hysteresis measurement can be stabilised, even in a magnetically open asymmetrical configuration, and give reliable values for the magnetic parameters [10], [12]. The results are obtained for industrial series of electrical steels with the magnetic properties varied in a broad range. Industrial potential of the suggested method is discussed in all technical details.

II. EXPERIMENTAL

Six different industrial grades of non-oriented (NO) electrical steels and six grades of grain-oriented (GO) electrical steels were used for the measurements [6]. The surface of the steel strips of standard sizes $300 \times 30 \times 0.25 - 0.5$ mm^3 was covered by an insulating coating of ~ 5 μm thickness, which considerably improves the magnetic properties due to introduced tensile stress. Two strips of each steel grade were magnetised by a large single yoke with the inner and the outer pole distances of 220 and 300 mm, respectively (see Fig. 1). An air gap between the yoke and the samples was varied in the range of 0–10 mm to check the method stability. The measurements were then performed with constant gaps of 3 and 5 mm for the NO and the GO steels, respectively. The SST measurements were also performed for comparison with the standard data using the second similar yoke.

The technical details of the setup were comprehensively discussed in our previous work [4]; only the necessary experimental parameters are specified and discussed below. The magnetic induction B was evaluated by a numerical integration of the signal induced in a sample-wrapping coil. The NO steels were measured with the fixed induction amplitudes $B_{max} = 1$ and 1.25 T; the GO steels – with $B_{max} = 1.25$ and 1.5 T at 50 Hz magnetisation frequency. These amplitude values correspond to the industrially attractive levels of low and middle saturations, at which the electrical steel products are usually operated. The experiments were repeated for the opposite sample side to verify the stability of direct field measurement. Two typical NO and GO steel strips were additionally tested in the wide ranges of induction amplitudes and magnetisation frequencies: $B_{max} = 0.1 - 1.5$ and $0.1 - 1.8$ T for the NO and the GO steels, respectively, at

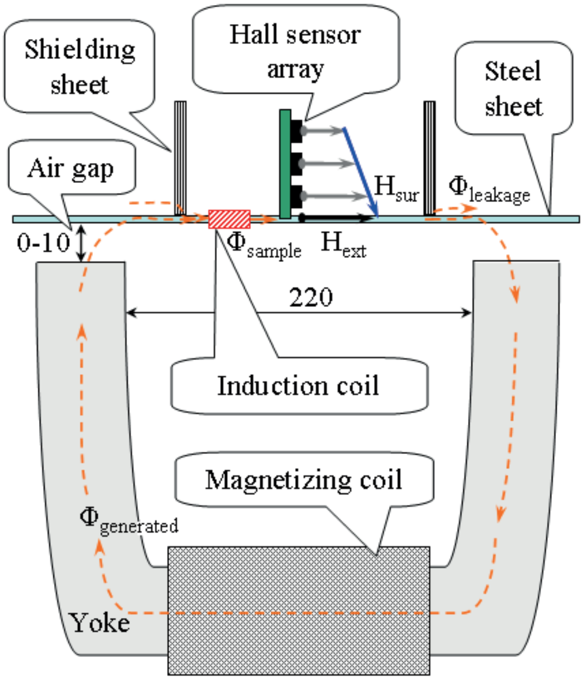
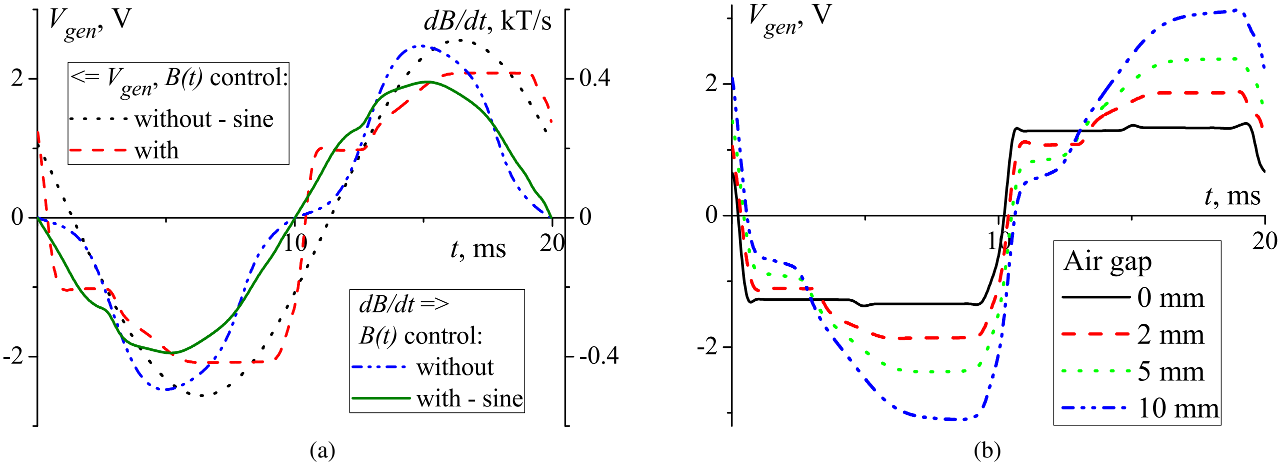


Fig. 1: Block scheme of the magnetising-sensing unit (shown sizes are in mm).

three different magnetisation frequencies $f = 25, 50$ and 100 Hz; $f = 1 - 100$ Hz at fixed $B_{max} = 1, 1.25$ and 1.5 T for the NO and the GO steels, respectively. The similar measurements with different B_{max} values were also performed for the magnetically softest NO steel and the magnetically hardest GO steel at 50 Hz magnetisation frequency.

All measurements were performed with and without the $B(t)$ waveform control. The $B(t)$ waveform was iteratively adjusted to the required sine curve by means of a digital feedback procedure. The generated voltage waveform $V^{'}_{gen}(t_j)$ at the next iteration step was calculated by time re-sampling of the same function $V_{gen}(t_j)$ at the previous step the way the corresponding measured induction waveform $B(t_j)$ is similarly time re-sampled to a required sine function $B^{'}(t_j) \sim \sin$ [2]. This old algorithm was additionally complemented by subroutines for simultaneous control of B_{max} and H_{max} amplitudes [4]. Performance of the feedback procedure is illustrated by Fig. 2; for better visualisation, the induced signal $B(t)/dt$, which should be actually adjusted according to the standards, is shown instead of the controlled $B(t)$ waveform. The used feedback procedure can alter the $V_{gen}(t)$ waveform of monotonic shape only; the algorithm fails if the $V_{gen}(t)$ waveform is degenerated into a square-wave. It is well seen at the points of maximal nonsinusoidal distortion of the $B(t)/dt$ signal in Fig. 2(a) and for the measurements with small gaps in Fig. 2(b). This led to a feedback algorithm failure for the softer GO steels with air gaps less than 3 mm; however, at this condition the $B(t)$ waveform was of sinusoidal shape even without the feedback control. The algorithm can also fail at high B_{max} amplitudes (high saturation level) because of a strong flat distortion of the $B(t)$ waveform from the required sine shape. The latter problem seems to be typical for many measurement systems and could be solved using a more sophisticated feedback algorithm with an additional phase correction [14].

A vertically mounted array of three Hall sensors was constructed to measure a tangential surface field profile. Hall chips with 5 mV/G sensitivity and about $0.1 \times 0.1\ \mathrm{mm}^2$ sensitive area from Allegro MicroSystems Inc were used. Noisy output signals from the Hall sensor were smoothed by an averaging over the subsequent magnetisation cycles: 3000 and 5000 cycles for the NO and the GO steels respectively. A recently introduced "shielding" approach was used for suppression of the field gradient. This approach uses two magnetically soft sheets from laminated GO steel, which force the magnetic leakage flux to flow



(a) (b)

Fig. 2: (a) Waveforms of the magnetising voltage $V_{gen}(t)$ (left scale) and the corresponding induced signal $B(t)/dt$ (right scale) with and without $B(t)$ waveform control. The measurements were done for the typical NO steel with 3 mm air gap, the higher amplitude $B_{max} = 1.25$ T and 50 Hz magnetisation frequency. After the feedback adjustment, the form factor of the controlled $B(t)$ waveform is 1.1116 and of the shown $B(t)/dt$ signal is 1.1083. (b) Typical adjusted waveforms of the magnetising voltage $V_{gen}(t)$ at the different air gaps. The measurements were performed with the same B_{max} amplitude and the sinusoidally controlled 50 Hz $B(t)$ waveform.

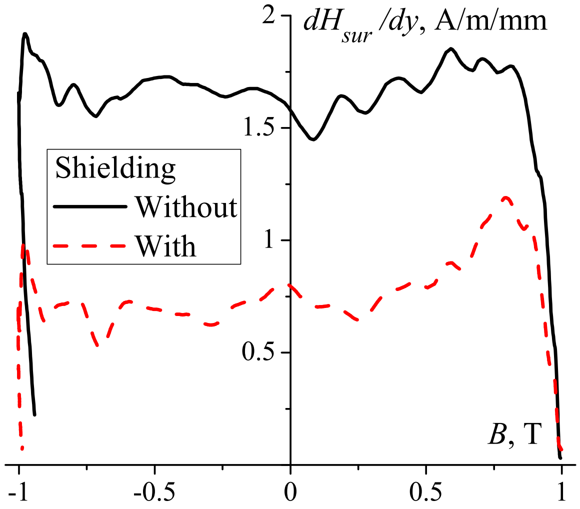
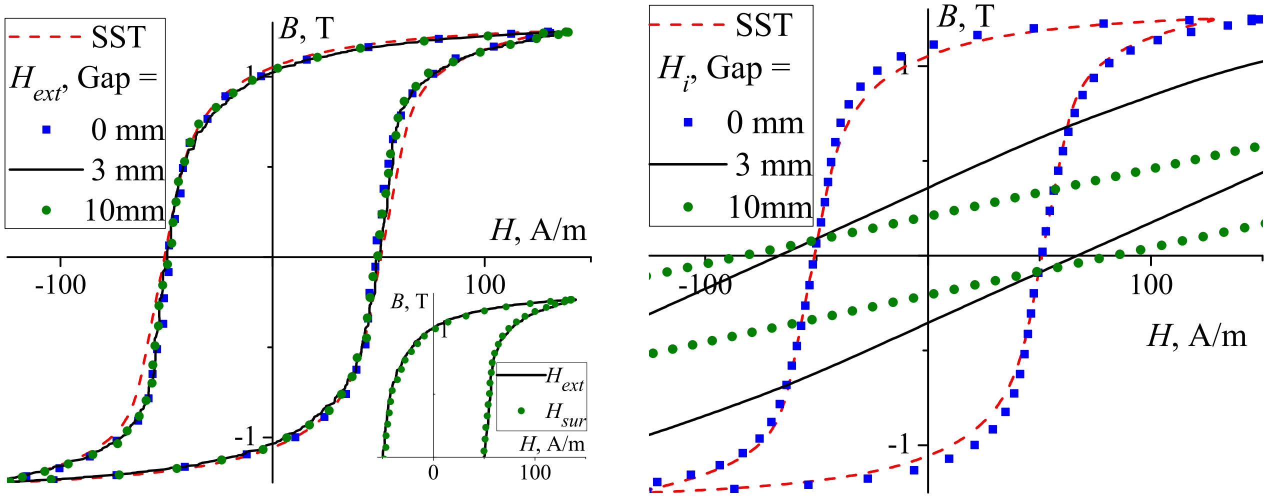


Fig. 3: Surface field gradients with and without the shielding as a function of B. The measurements were done for the typical NO steel with $B_{max} = 1$ T.

through the sample [11]. As shown in Fig. 3, the shielding reduced the field gradient by 50%. Without the shielding, the gradient was also low at the yoke-free sample side because the steel strip itself acted as a magnetic shield [13]. The actual sample field was determined by linear extrapolation of the measured field profile to the sample face (see Fig. 1) [1], [6], [10]. All magnetic parameters were evaluated for three different methods of field determination: the extrapolated field H_{ext}, the surface field H_{sur} measured by the closest Hall sensor at 1.5 mm distance above the sample, and the standard current field $H_i = NI/l_m$ (N is the number of turns of the magnetising windings, I is the magnetisation current read from a shunt resistor, and $l_m = 220$ mm is the inner distance between the yoke poles by analogy with the SST standard).



(a)

(b)

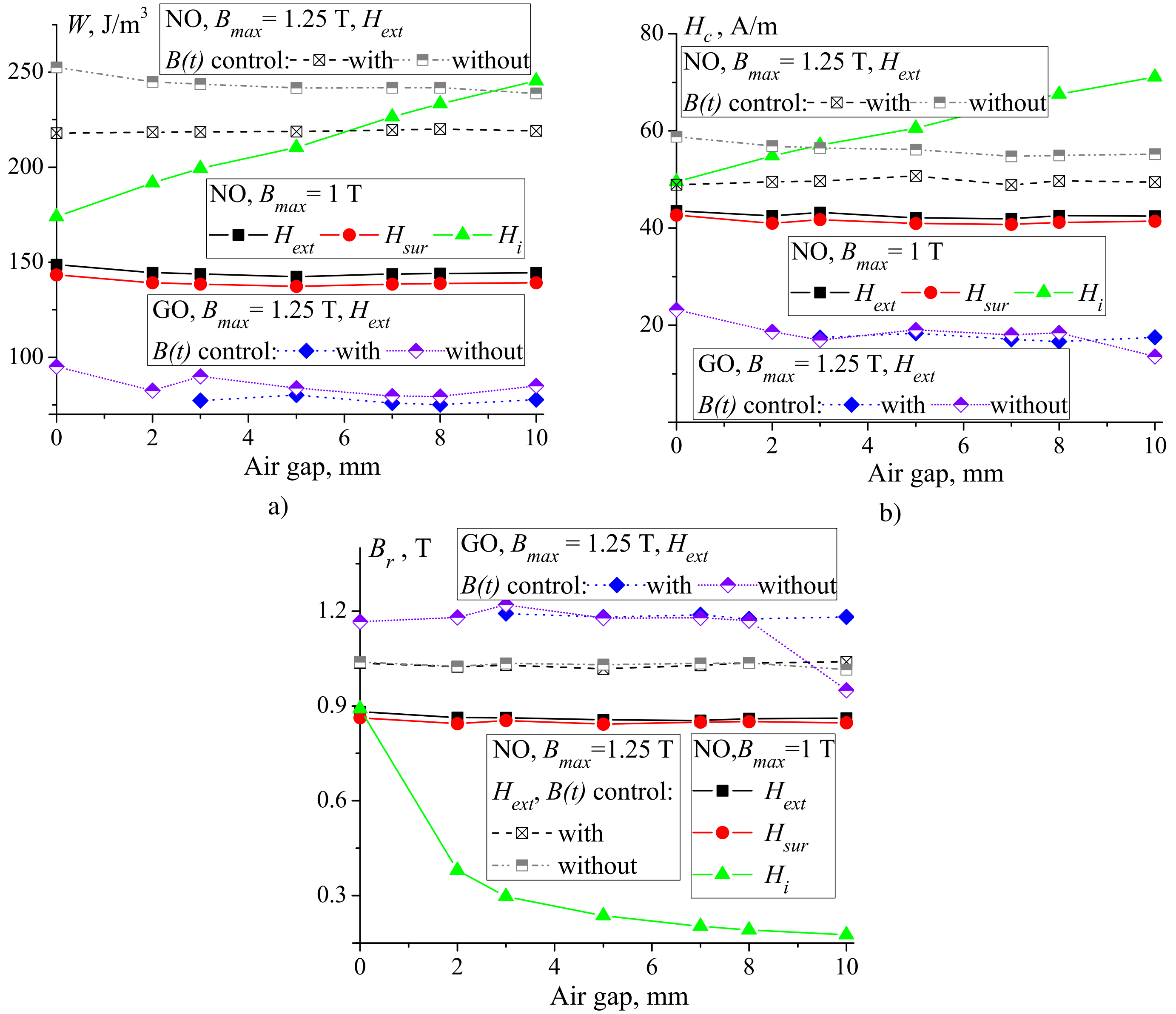
Fig. 4: Hysteresis loops of the typical NO steel measured by the standard SST and the single-yoke setup with different air gaps as functions of the extrapolated H_{ext} (a) and the current H_i (b) fields. The inset of Fig. 4(a) shows the loops measured with 3 mm gap as functions of the extrapolated H_{ext} and the surface H_{sur} fields. The H_i scale for the zero gap loop in Fig. 4(b) is shortened to 8% for better comparison with the SST data.

III. RESULTS

A. *Stability with yoke lift-off*

The principal advantage of the proposed measurement method is that it provides repeatable results with respect to variations in the experimental conditions [4], [10]. This is illustrated by Figs. 4 and 5, which present the hysteresis loops and the basic magnetic parameters at different air gaps between the yoke and the steel strips. The hysteresis loops in the H_{ext} representation do not change with gap variation, while the H_i loops are substantially inclined due to the demagnetising effect (see Fig. 4) [2]. The H_{sur} representation gives very similar results to the H_{ext} data because of small H_{sur} gradients (see Figs. 3 and inset of Fig. 4(a)). There is a small difference between the H_{ext} and the SST loops in the first and the third hysteresis quadrants. The H_i loop with no air gap becomes similar to the SST loop at the magnetic path l_m elongated to 8% (see Fig. 4(b)). As opposed to the similar measurements with a sample-wrapping magnetisation coil, the H_i loops measured with air gaps cannot be accurately transformed to the corresponding loop measured without the gap by further corrections of $l^*_m = k_l l_m$ and by introduction of the demagnetisation factor N_d: $H_{cor} = H_i/k_l - N_d B/\mu_0$ [4].

Our observations are supplemented by the dependence of classical magnetic parameters on the gap distance (see Fig. 5). The results are presented for the classical hysteresis parameters: the loss W, the coercive force H_c and the remanent induction B_r. W is the principal parameter describing the electrical steel efficiency. The coercive force H_c shows similar relations for the electrical steel loops with a square shape. The classical remanent induction B_r is an important characteristic for steel magnetisation ability; its precise evaluation is of interest to industry [6]. Dependence of the magnetic parameters in the direct field representations H_{ext} and H_{sur} are stable with the gap and again very similar; there is only small quantitative shift in the field scale (see Fig. 3). However, the H_i data are highly dependent on the gap distance. The measurements without the $B(t)$ control lead to an additional result scattering. For homogeneous magnetisation of the strip center, the minimum inner distance between the yoke poles should be about 100 mm (see Fig. 6).



a)

b)

c)

Fig. 5: Stability of the hysteresis loss W (a), the coercive field H_c (b) and the remanent induction B_r (c) with the air gap for the typical NO and GO steels and different experimental conditions. Curves for the NO steel are shown for all three methods of field determination for $B_{max} = 1$ T; the data for higher $B_{max} = 1.25$ T are shown for the H_{ext} representation only with and without the $B(t)$ waveform control. Curves for the GO steel with and without the $B(t)$ waveform control are also shown for the H_{ext} representation and $B_{max} = 1.25$ T.

B. Correlation with SST data

For applicability of the proposed measurement technique in practice, our physically accurate data should correlate with the standard Epstein/SST values [2]–[7]. As shown in Figs. 7–10, strong linear correlations were experimentally observed, at least for the magnetically harder NO steels. The error bars in these figures were evaluated as the standard error of two identical tests from the opposite sample sides. Data for the two strips of the same grade were presented separately because the difference between their magnetic properties can be comparable to the difference 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

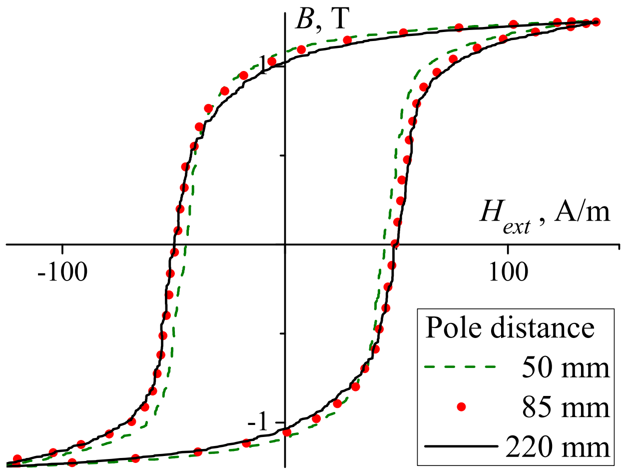
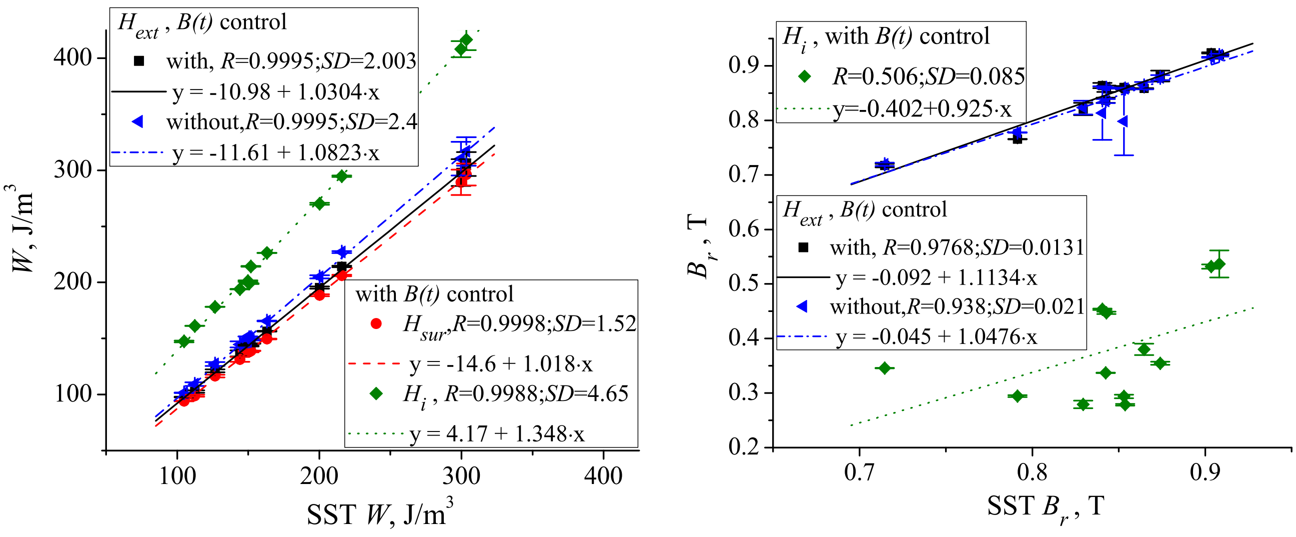


Fig. 6: Hysteresis loops of the typical NO steel measured by the single yokes with different inner distances between the yoke poles. The measurements were performed with 3 mm gap between the yokes and the sample.



(a) (b)

Fig. 7: Relations of the hysteresis loss W (a) and the remanent induction B_r (b) with the correspondent SST parameters for the series of NO steels. The curves are shown for all three methods of field determination for $B_{max} = 1$ T. Additionally, the H_{ext} data are shown with and without the $B(t)$ waveform control. The B_r curves for the H_{sur} representation is omitted for the sake of simplicity. The error bars are evaluated as the standard error of two identical tests from the opposite sample sides. 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.

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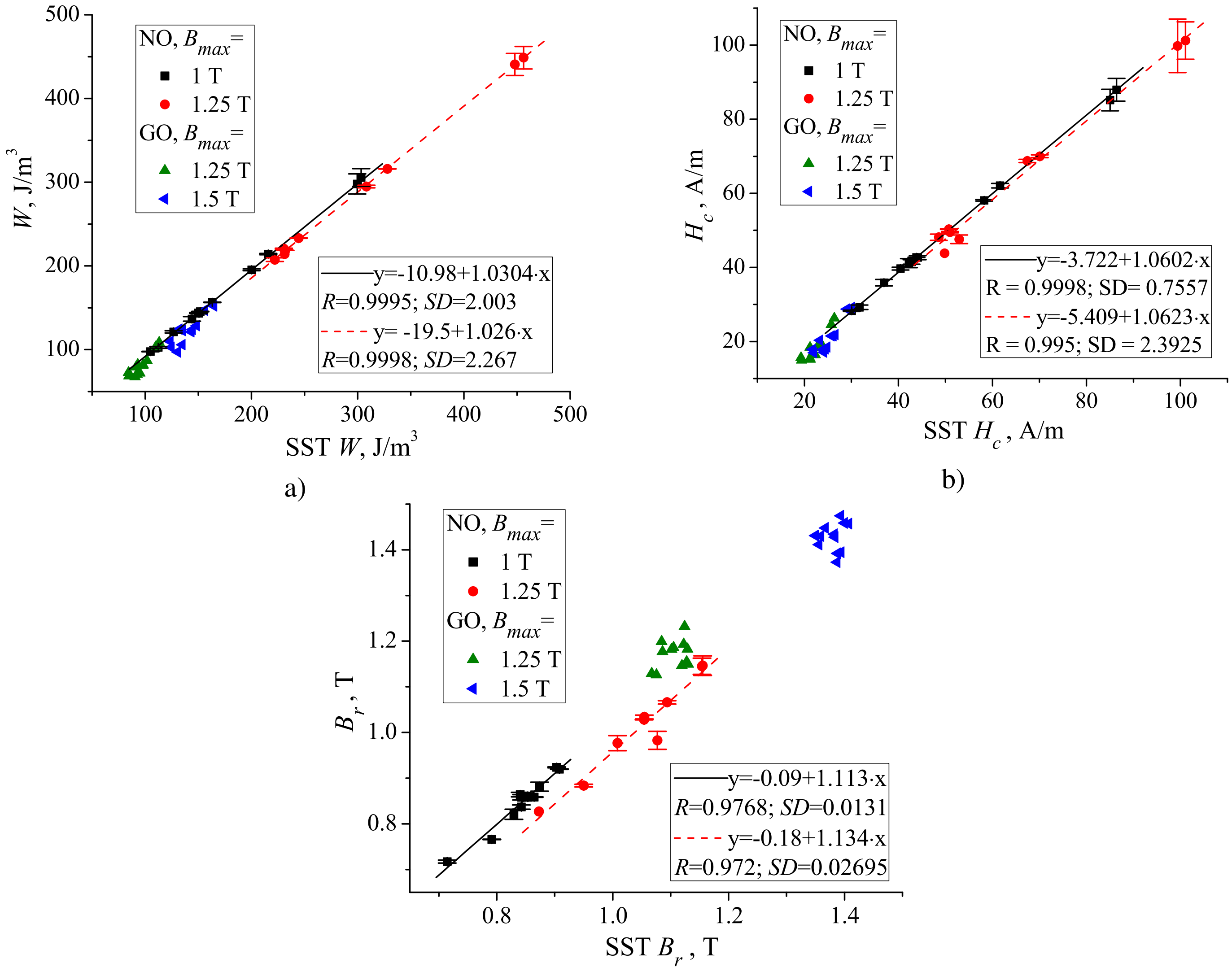
The direct field H_{ext}/H_{sur} data provide excellent linear correlation with practically unit slopes for the W/H_c parameters of the NO steels even without the $B(t)$ waveform control. The offsets of the linear correlations, however, are far from zero. The unstable H_i data also show a strong linear correlation, though with a higher slope. However, the B_r parameter cannot be evaluated using the H_i method, and it is more sensitive to the $B(t)$ waveform variations (see Fig. 7) [12].

The H_{ext} results shown together for all steels prove this trend but also demonstrate a shift of the



a)

b)

c)

Fig. 8: Relations of the hysteresis loss W (a), the coercive field H_c (b) and the remanent induction B_r (c) with the corresponding SST parameters for both steel series and induction amplitudes B_{max}. The curves are shown for the extrapolation field method H_{ext} with the $B(t)$ waveform control.

correlation offsets at different B_{max}. The magnetic parameters of the softer GO steels seem to follow the linear correlations of the NO steel data but with higher scattering (see Fig. 8). Higher data scattering is better illustrated in Fig. 9. The correlation of the H_{ext} data is worse than the correlation of the H_i data for the GO steels. A measurement error of a few A/m becomes comparable to the range of parameter variation. For the GO steels, the B_r correlation in a lower variation range is not observable at all due to higher measurement error.

However, the additional measurements with different induction amplitudes B_{max} and magnetisation frequencies f verify the reliability of our experimental data. With wider range of parameter variation, good linear correlations to the corresponding SST quantities were obtained for the GO steels as well (see Fig. 10). Because of the above-mentioned feedback failure at high saturation level, the correlation linearity is kept until $B_{max} < 1.4$ and 1.7 T for the NO and the GO steels, respectively. The correlations are independent of the magnetisation frequency. However, the slopes of the W/H_c correlations significantly decrease from ~ 1 for the typical NO steel to $0.8 - 0.9$ for the softer GO steel. Additional measurements of the magnetically softest NO steel and the hardest GO steel prove this trend: the softer the material,

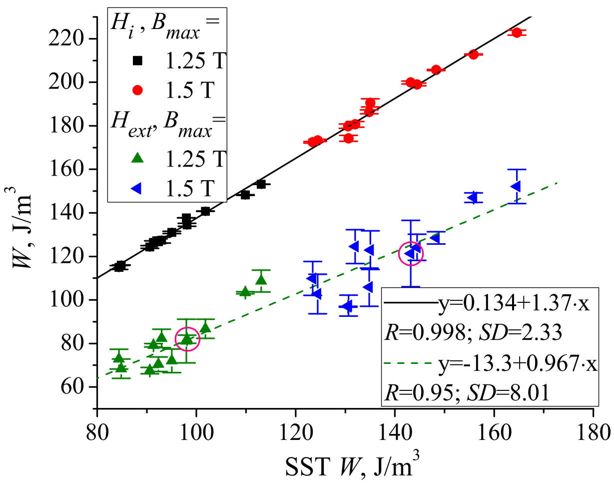


Fig. 9: Relations of the hysteresis loss W with the corresponding SST data for the series of GO steels. The data for both induction amplitudes $B_{max} = 1.25$ and 1.5 T are shown for the current H_i and the extrapolation H_{ext} methods of field determination. Circles show the steel with considerably larger grains.

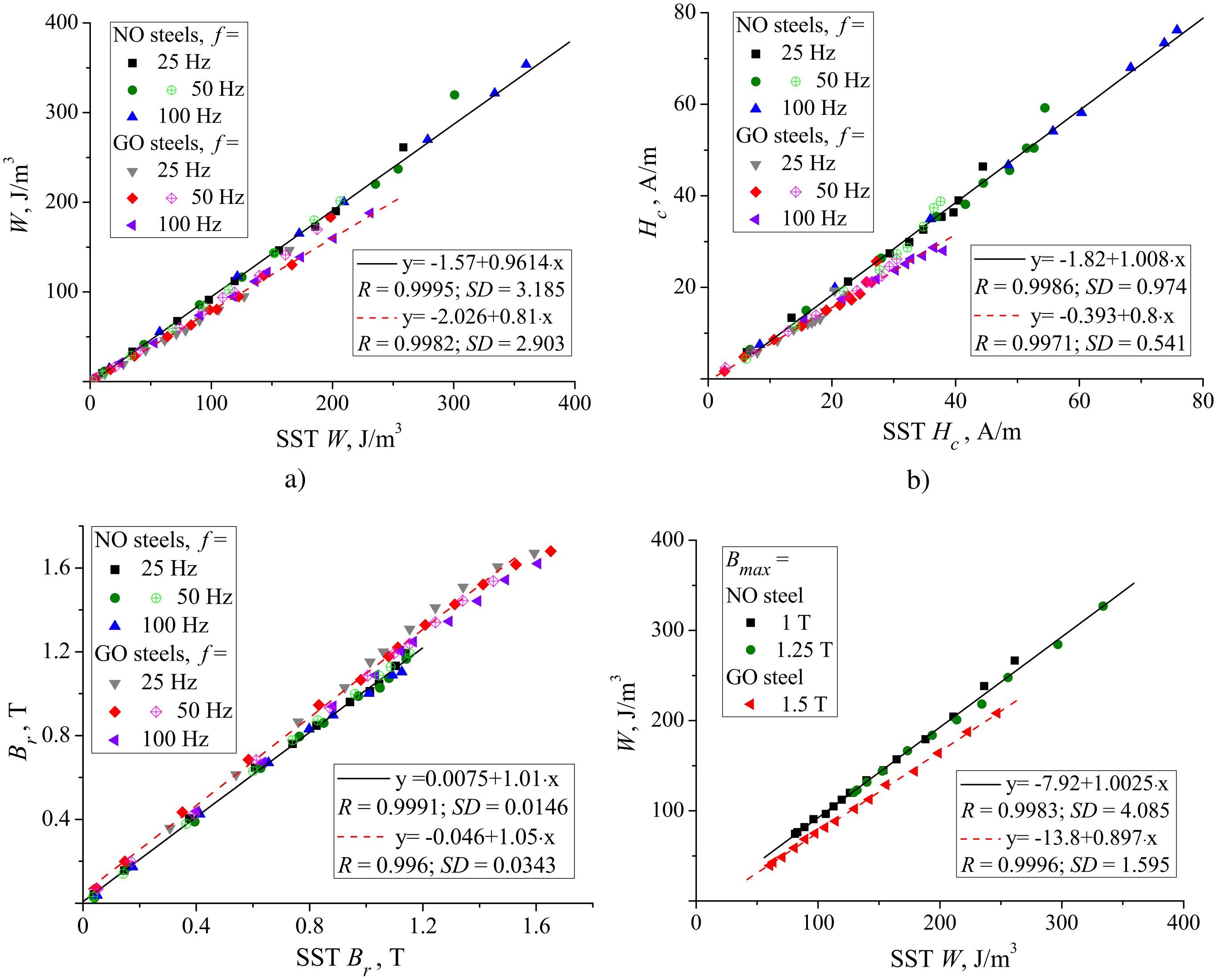
the smaller the slope.

IV. DISCUSSION

The concept of simultaneous control of both magnetisation waveforms $H(t)$ and $B(t)$ is absolutely clear from a physical point of view. Moreover, this *physically correct* method should be used to obtain the basic reference data. However, this concept has not been widely implemented in practice and recommended by the standards [2], [3], [8]. This is due to technical complications with the application of the direct field approach as well as conservative adherence to the standard current field method. This work confirmed that the proposed method enables to provide *repeatable* and *reliable* data with sufficient correlation to the standard SST values (see Figs. 4–10) [4], [12]. However, the main two obstacles for its industrial implementation are still (i) choice of a suitable field sensor, and (ii) imperfect correlation with the standard values.

Fast and accurate measurement of low magnetic fields is currently a serious problem. The modern Hall elements used have the necessary sensitivity of several mV/G, but their output is too noisy. To suppress noise, we average the data over several thousands magnetisation cycles to obtain a smooth hysteresis loop for the electrical steels at 50 Hz magnetisation. This increases the testing time up to several minutes, which is suitable for laboratory measurements, but not for industrial on-line testing. However, this work is focused on the experimental confirmation of potential applicability of the proposed technique. The choice of a suitable field sensor is a separate serious task. A standard H-coil and a Rogowski-Chattock potentiometer, with their well-known intrinsic drawbacks (calibration complexity, accurate integration of low induced signal, and so on), have been used for decades without any similar finding [2], [4], [9]. Modern magnetoresistive and fluxgate sensors can be more applicable for industrial purposes due to their high sensitivity and lower output noise [15]–[17].

Besides the sensitivity-noise characteristics, the size of the sensor chip and its sensitive area are important parameters. An area of linear field gradient was found to stretch to 5–7 mm above the sample for our magnetisation system. Because of this, it would be optimal to use two field sensors at a maximum distance of 4–5 mm above the steel strip. The first sensor should be positioned as close as possible to the sample. With a low field gradient, significant simplification of the setup is acceptable. In this situation, as in the considered case of the single-yoke system, only one field sensor can be sufficient for relatively accurate evaluation of the magnetic parameters (see Figs. 3, 5, 7(a) and inset of Fig. 4(a)). However, high surface field gradients can be a serious source of the measurement error as in the case of open rotational SST [3], [8], [13].



a) b)

c) d)

Fig. 10: Relations of the hysteresis loss W (a), the coercive field H_c (b) and the remanent induction B_r (c) with the corresponding SST parameters for different induction amplitudes B_{max} and magnetization frequencies $f = 25, 50$ and 100 Hz. Two typical NO and GO steel strips (solid symbols), the magnetically softest NO steel (open circle) and the magnetically hardest GO steel (open diamond) were tested. (d) Similar relations of the hysteresis loss W for different magnetisation frequencies f and induction amplitudes $B_{max} = 1, 1.25$ and 1.5 T for the typical NO and GO steels, respectively. The curves are shown for the extrapolation field method H_{ext} with the $B(t)$ waveform control. The lines present the linear fits of the typical steel data.

The sensitivity area of field sensor is connected to a disputable issue of magnetisation homogeneity inside and between large grains of the electrical steels [6], [15]. For the investigated NO and GO steels with the mean grain size of 0.1 and $5 - 10$ mm, respectively, the H_c experimental standard error of the opposite side measurements in the H_{ext} representation is approximately 1 A/m. For the W data, the error is higher for the GO steels: ~ 5 against ~ 3 J/m^3. Moreover, for the specific grade of GO steel with 3 cm grain size shown in Fig. 9 with circles, the error is three times higher. This shows higher magnetisation inhomogeneity and higher instability of the measurement conditions for the GO steels. Therefore, a field sensor with a larger sensitive area or a horizontally mounted sensor array should be better for more stable measurements [15].

It is clear that repeatability of the measurements is also dependent on stability of the magnetisation waveform. The discussed circumstance of single yoke magnetisation needs the specific $V_{gen}(t)$ waveform to keep $B(t)$ of sinusoidal shape. However, the initial $B(t)$ distortion seems to be less important for the measurement repeatability than the accurate field determination (see Fig. 2(a)). This leads to an interesting experimental finding that the measurement technique can also give reasonable and stable results without the additional $B(t)$ adjustment procedure, at least for W and H_c data [12]. Another surprising fact is that the current field H_i method can be used for relatively accurate evaluation of W and H_c values too, but only for the fixed gap distance (see Figs. 5 and 7).

The second technical problem of imperfect correlation with the standard values is physically well-grounded. Even the standard methods are not perfect. The intrinsic sources of error are the uncontrollable contact quality between the constituents of the magnetic circuit and the differently defined constant magnetic path l_m used for the H_i calculation. Therefore, there is an imperfect correlation between the standard Epstein and SST data too, which retards the replacement of the outdated Epstein frame by SST in practice [2]–[4]. Moreover, our SST measurements were done with the small air gap because of the strip insulation coating. This increases the magnetic path l_m and introduces an additional error due to the magnetic circuit inhomogeneity (see Fig. 4(b)). Even in the ideal case of absolutely accurate direct field measurements, the correlation with the standard SST values would be qualitatively the same and also dependent on the B_{max} level (see Fig. 8). The significant decrease of the W/H_c correlation slopes for the GO steel data can be also caused by higher effective value of the magnetic path $l_m \simeq 245 - 275$ mm (see Fig. 10).

The imperfect correlation is caused by the difference between the SST and the H_{ext} hysteresis loops, illustrated in Fig. 4(a). Besides the above-mentioned imperfections of SST results, this difference can be caused by a nonuniform magnetisation of the steel bulk due to the substantial air gap, the asymmetrical single-yoke configuration, or eddy currents [3]. This hypothesis is additionally supported by measurements with other magnetisation system with higher field inhomogeneity (Helmholtz type solenoid): the difference was qualitatively similar but quantitatively more pronounced [4], [12]. However, the asymmetrical single yoke with much larger pole thickness as compared with that of the steel strips is supposed to magnetise the samples nearly homogeneously, which was proved experimentally in our previous work [13]. This assumption was also supported by the presented data, which showed good stability of the results with the yoke lift-off (see Figs. 4 and 5). Increase of the air gap between the yoke and the sample should logically lead to more nonuniform magnetisation. For homogeneous propagation of the yoke-generated magnetic flux inside the sample depth, the distance between the yoke poles should be also large enough (see Fig. 6).

The results can be additionally influenced by errors stemming from the technically complex method of direct field measurements: calibrations of sensitivity and spacial arrangement of the Hall sensors, their accurate positioning perpendicular to the magnetisation line, deviation of the surface field gradient from the linear dependence, local manufacturing deviations of the steel magneto-mechanical properties, parasitic Earth magnetic field, and so on [4], [10]. Despite these numerous sources of measurement error, the standard error of direct field data is comparable with that of H_i data for the NO steels (see Fig. 7). This is a good indicator of acceptable accuracy level for the direct field measurements.

Unfortunately, this accuracy level is not sufficient for precise evaluation of the GO steels. Due to the above-mentioned magnetisation inhomogeneity, the standard error of H_{ext} data is already 2–3 times higher than that of the H_i data. Combined with a lower range of parameter variation, this leads to worse linear correlation with the SST values (see Fig. 9). However, this is believed to be the true trend. Both lower B_{max} values for the NO and the GO steels correspond to the same saturation stage: the knee of the hysteresis loop is hardly visible and the higher B_{max} values are similarly 0.25 T higher (middle saturation level). It is shown in Fig. 8 that the data for the GO steels are in line with the pronounced linear tendencies of the data for the NO steels for the same saturation stages. The obtained results for the GO steels are clearly reliable, and the described method can be used for rough evaluation of the magnetic properties (see Fig. 10). Accurate measurement with error comparable to the H_i approach requires a low-noise field sensor with larger sensitive area [15].

V. CONCLUSION

The physically based measurements with control of the induction waveform and simultaneous direct determination of the magnetic field were proven to provide stable results with a strong linear correlation to the standard data of the single sheet tester. The experiments were performed for the industrially attractive case of single-yoke magnetisation through a substantial air gap. However, the correlation with the standard data is non perfect. The slope of the linear fit is close to one, but the offset is non-zero and dependent on the tested magnetic parameter and the induction amplitude. Practical implementation of the technique requires another low-noise field sensor with the sensitive area up to several cm in size.

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