

Investigating the applicability of the Magnetic Adaptive Testing method for non-destructive testing of materials on magnetically open samples

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Within the framework of the Magnetic Adaptive Testing (MAT) method, a new approach based on measurements performed on magnetically open samples is verified, which is essential for the industrial application of the method. The common challenges associated with open-sample measurements were investigated, particularly the relationship between the magnetizing current and the magnetic field intensity in the sample, which is expected to be non-linear and was confirmed experimentally. MAT addresses this issue through the relativization of measured values after load application with respect to the initial values obtained before loading. Furthermore, since the magnetic flux density in the tested material is determined indirectly from the voltage induced in a coil placed on the magnetizing yoke, the relationship between the magnetic flux in the sample and in the yoke was examined and found to be sufficiently coupled.

Keywords: non-destructive testing, magnetic adaptive testing, conventional magnetic parameters, magnetically open samples

1 Introduction

Magnetic Adaptive Testing (MAT) is a promising method in non-destructive evaluation of materials, capable of detecting microstructural changes even at a microscopic scale. Its sensitivity to subtle changes in magnetic properties makes it particularly suitable for early detection of stress, fatigue, or degradation of ferromagnetic materials. The principles and capabilities of the MAT method have been investigated in numerous experimental studies [1-12]. However, its applicability to magnetically open samples has not yet been sufficiently investigated, although this represents a crucial step toward industrial implementation. A major challenge of an open magnetic configuration is the non-linear relationship between the magnetizing current and the magnetic field intensity in the sample. Moreover, since the magnetic flux in the sample is determined indirectly by means of a sensing coil wound on the magnetizing yoke, it is necessary to clarify the relationship between the magnetic flux in the sample and that in the yoke.

One possible approach to describing the current – field dependence is the extrapolation method reported in, eg, [13-15], which, however, appears inefficient and/or unnecessarily complex for application within MAT. Instead, the magnetic field intensity was measured at different positions relative to the sample using a Hall probe. The coupling between the magnetic flux in the sample and in the yoke was verified by comparing signal waveforms obtained from sensing coils placed both on

the magnetizing yoke and directly on the sample. The aim of this study is to experimentally verify these relationships and assess the applicability of MAT in magnetically open configurations.

2 Theoretical background and methodology of magnetic adaptive testing

The principle of the Magnetic Adaptive Testing (MAT) method is based on the measurement of a series of minor hysteresis loops using a triangular excitation field. Material changes are assessed via the magnetic parameter known as a differential permeability, defined as the slope of the tangent to the hysteresis loop at a specific point (k -th). This point is determined from the hysteresis loop with the time t as the parameter in the HB space representation. Thus, the differential permeability at a given instant of time ($t = t_k$) can be expressed by the following relation

$$\mu_{diff}(H_k, B_k) = \frac{1}{\mu_0} \frac{dB(t)}{dH(t)} \bigg|_{\substack{H_k=H(t=t_k) \\ B_k=B(t=t_k)'}}$$

where μ_0 is magnetic constant (permeability of free space). To simplify the evaluation of differential permeability, the magnetizing process is carried out so that the rate of change of the magnetic field intensity remains constant $|dH(t)/dt| = c$. Under this condition, the differential permeability can be determined directly from the

induced voltage signal, avoiding complicated numeric calculations. Using the Faraday's law of electromagnetic induction which links the relation between induced voltage and flux density, the above expression can be rearranged as follows:

$$\mu_{diff}(t) = \frac{1}{\mu_0} \frac{\frac{dB(t)}{dt}}{\frac{dH(t)}{dt}} = \frac{1}{\mu_0} \frac{\left| \frac{dB(t)}{dt} \right|}{c}.$$

The term $dB(t)/dt$ can be expressed through the voltage induced in the pick-up coil $v_{ind}(t)$. For a coil with N_2 secondary turns and cross-sectional area A , the relationship can therefore be written as

$$\mu_{diff}(t) = \frac{1}{\mu_0} \frac{\left| \frac{dB(t)}{dt} \right|}{c} = \frac{1}{\mu_0 N_2 A c} |v_{ind}(t)|.$$

This relation indicates that the relative differential permeability is proportional to the absolute value of the induced voltage. Therefore, in practical MAT measurements it is sufficient to measure the time dependence of the induced voltage in the pick-up coil, which, when processed using appropriate MAT evaluation procedures, enables the assessment of micro-structural changes in the material.

Minor hysteresis loops are measured using a gradually decreasing amplitude of the magnetic field intensity H . This approach entirely eliminates the need for a demagnetization of the specimen prior to the measurement. Precise demagnetization is usually a demanding procedure, since it must be carried out with smoothly decreased field amplitude at low frequencies, in order to avoid the influence of eddy currents. Failing to do so can, under certain circumstances, even lead to a higher remanent state than before the demagnetization was applied.

The evaluation of the measured data is performed in several steps. First, the measured data are interpolated to predefined values of the magnetic field intensity, which enables the construction of triangular matrices. In these matrices, the vertical axis corresponds to the excitation amplitude associated with a particular minor hysteresis loop, while the horizontal axis represents the field amplitudes for which the values of differential permeability are interpolated. Since the excitation amplitude decreases for successive minor hysteresis loops, the number of interpolated values decreases in each row, resulting in the triangular shape of the matrix.

After obtaining the set of minor hysteresis loops, the specimens subjected to a defined load (either thermal, or mechanical, or even neutron irradiation) to introduce microstructural changes, related to, *eg*, thermal stress-relief annealing, fatigue- or irradiation-induced defects in the crystalline lattice, *etc*.

This measurement procedure is repeated after each loading step, yielding one triangular matrix for every applied load. These matrices are subsequently arranged into a three-dimensional array, where each layer corresponds to a particular loading state. The obtained values are then normalized with respect to the initial measurement in order to eliminate systematic errors and reduce the need for highly precise calibration of the measuring apparatus. Consequently, the evaluation focuses on the relative changes in differential permeability caused by the applied load. Thus, we can obtain calibration curves, representing the relationship between the (known) applied load and the differential permeability. More detailed descriptions of the MAT method can be found in several previous studies [1-4].

3 Experimental setup

For measurements on magnetically open samples, a measurement apparatus similar to that previously used for magnetically closed samples was employed [2]. The magnetic circuit consisted of a C-shaped yoke with primary (excitation) and sensing coils. The sample – a rectangular prism like a standard Charpy V-notch specimen – was also fitted with its own sensing coil. The excitation signal was generated using an arbitrary waveform generator connected to a high-power operational amplifier, which produced the triangular magnetizing current required for MAT measurements, resulting in a triangular time dependence of the magnetic field intensity $H(t)$. The operational amplifier was configured as a voltage-to-current converter, using a high-precision calibration resistor in the feedback loop to ensure accurate control of the excitation current and facilitate current sensing. The applied magnetic field and the induced voltage are measured simultaneously using a four-channel, synchronously sampled data acquisition (DAQ) system with a sampling rate of 800 kHz. All instruments were controlled by dedicated software, which managed the measurement parameters, timing, data acquisition, and storage. Since we needed to measure two induced voltages (that of the sample and of the yoke), the multichannel DAQ was utilized to get three synchronously sampled signals, corresponding to the exciting current and two induced voltages.

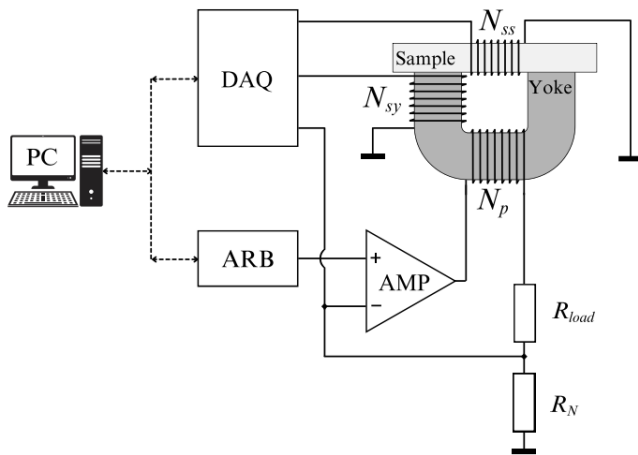


Fig. 1. Block diagram of experimental setup

To bring the sample into a defined magnetic state and to ensure symmetry of the hysteresis loop, a pre-magnetization procedure along the maximum hysteresis loop was applied prior to each measurement. For pre-magnetization, several cycles of the excitation field (or, the current) with the same parameters (*ie*, amplitude, frequency, and triangular waveform shape) were applied to the sample. While demagnetization is commonly used as the initial state, it requires a large number of cycles with gradually decreasing amplitude and is therefore more time-consuming.

4 Relationship between magnetizing current and magnetic field intensity in the sample

In measurements performed on magnetically open samples, the relationship between the magnetizing current and the magnetic field intensity in the sample is not straightforward due to the non-closed magnetic circuit [3, 4, 16]. The main objective of this part of the experiment was to verify whether conventional magnetically closed circuits can be replaced by open configurations while still obtaining comparable and reliable measurements. To investigate this dependence experimentally, the measurements were performed using a Hall probe positioned inside the sample in both longitudinal and transverse directions, as well as above and below the sample. In one sample, a hole was drilled in the longitudinal direction and in the other in the transverse direction, as illustrated in the schematic diagrams in Figs. 2a. and 2b. The relatively large diameters of the

holes were determined by the construction of the precise (calibrated and temperature-compensated) Hall probes available for the measurements. Before calibration, 10 pre-magnetization cycles of a triangular waveform (amplitude 2.5 A, frequency 1 Hz) were applied to the magnetic circuit to establish defined initial conditions. Subsequently, a calibration cycle was performed using a step-wise DC current increasing from 0 A to 2.5 A, decreasing to -2.5 A, and returning back to 0 A, in increments/decrements of 0.5 A. At each step, the corresponding DC magnetic field intensity was measured.

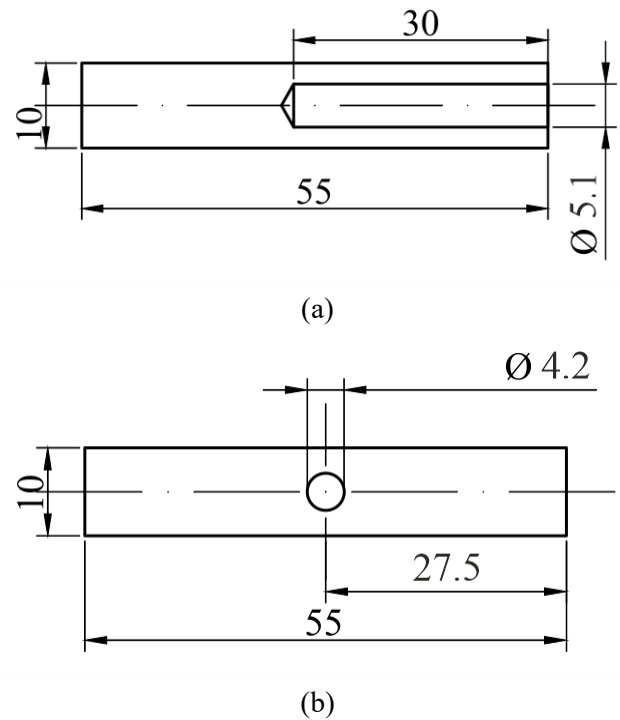


Fig. 2. Schematic diagram of the sample showing the hole drilled: (a) in the longitudinal direction, (b) in transverse direction

These measurements were performed for each of the described configurations with an air gap between the yoke and the sample of 0.0 mm, 0.1 mm, and 0.2 mm. The defined air gap was ensured using plastic foils of precise thickness, applied in one or two layers. The resulting dependencies (calibration curves) are presented in Fig. 3.

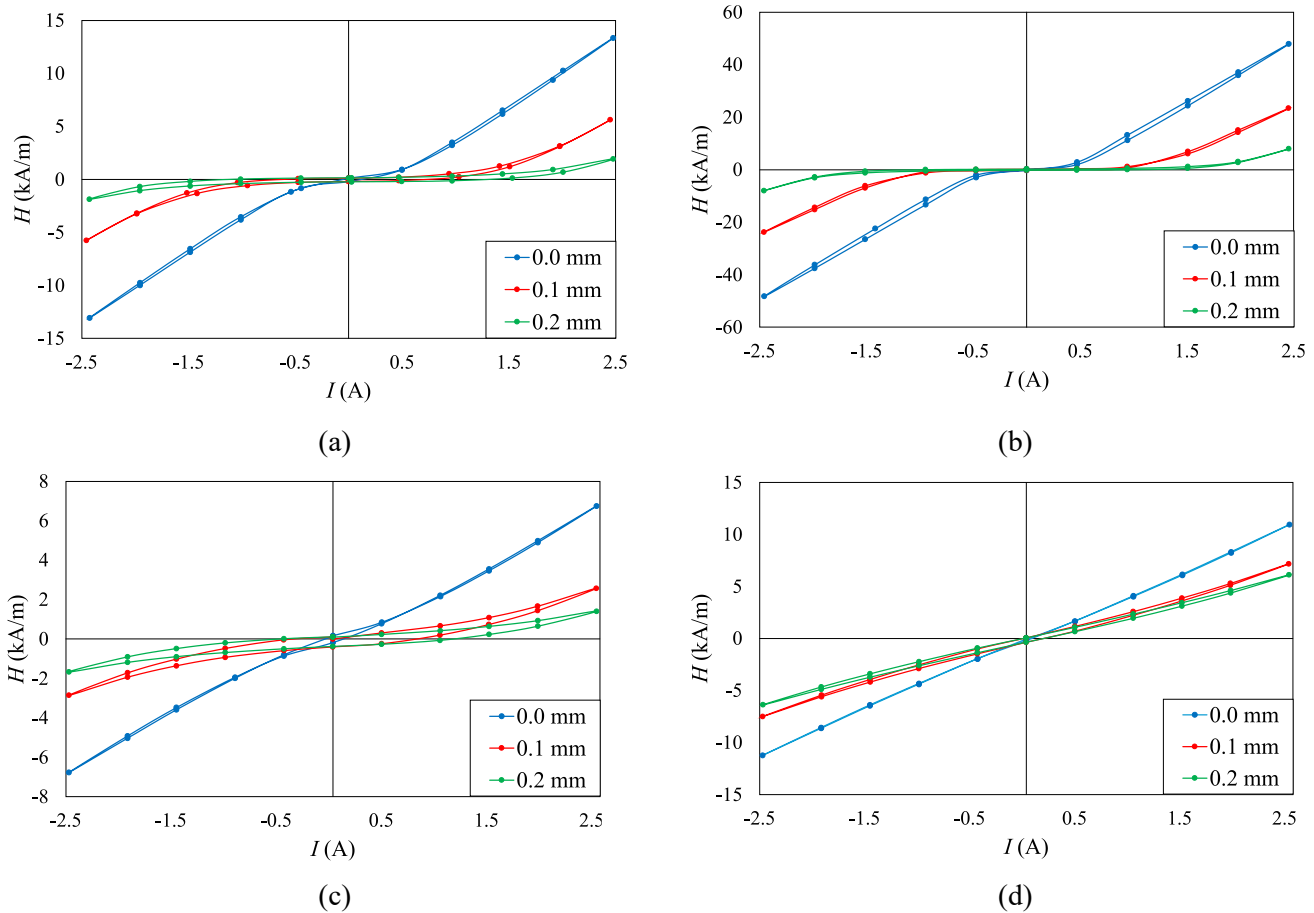


Fig. 3. Dependence of the magnetic field intensity in the sample on the excitation current. The Hall probe was positioned (a) longitudinally in, (b) transversely in, (c) transversely above, (d) transversely below the sample.

Based on the obtained dependencies, the influence of the Hall probe position relative to the sample on the measured values can be observed. These differences are illustrated in Fig. 4, showing that the highest magnetic field intensity was measured when the Hall probe was positioned transversely through the sample, compared to the other probe positions.

The results of these experiments indicate that, under certain conditions, the relationship between the excitation current and the magnetic field intensity can be significantly non-linear, and hysteresis may also occur. This non-linearity poses a major limitation for the calibration of measurement systems with magnetically open samples. This issue has been investigated in several previous studies as well, [3, 14, 15, 17]. The MAT method provides a solution to this issue by evaluating the data through normalization (or, relativization) with respect to the initial measurement prior to any load applied, allowing the monitoring of relative changes and effectively eliminating calibration problems.

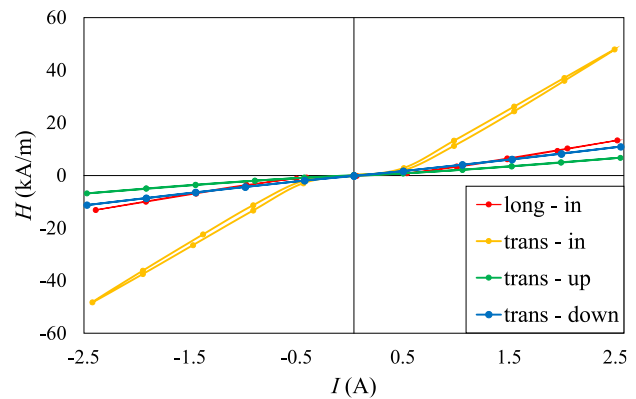


Fig. 4. Dependence of the magnetic field intensity in the sample on the excitation current – comparison for different Hall probe positions with a 0.0 mm air gap

5 Correlation between magnetic flux in the sample and in the yoke

Similarly to the case of a magnetically closed sample, the induced voltage is measured using a sensing coil. Based on the principle of the MAT method, the magnetic flux can be expressed in terms of the induced voltage, which can be applied both to the yoke and to the sample. Using the general relation, following from Faraday's law of induction, we obtain

$$v_{ind,y}(t) = N_{sy}A_y \frac{dB_y(t)}{dt}$$

$$v_{ind,s}(t) = N_{ss}A_s \frac{dB_s(t)}{dt},$$

where N_{sy} and N_{ss} is the number of turns of the sensing coil (first index s) on the sample or yoke (second index s or y), A_s and A_y is the cross-sectional area of the sample or yoke, respectively. This can be rearranged as

$$\frac{dB_y(t)}{dt} = \frac{v_{ind,y}(t)}{N_{sy}A_y},$$

$$\frac{dB_s(t)}{dt} = \frac{v_{ind,s}(t)}{N_{ss}A_s}.$$

By integrating these relations, the magnetic flux can be expressed as a function of the induced voltage

$$\Phi_y(t) = B_y(t)A_y = \frac{1}{N_{sy}} \int v_{ind,y}(t) dt$$

$$\Phi_s(t) = B_s(t)A_s = \frac{1}{N_{ss}} \int v_{ind,s}(t) dt$$

Therefore, by measuring the induced voltage in the sensing coils placed on the sample and on the yoke, information about the magnetic flux can be obtained. The samples were measured using a triangular current waveform with a decreasing amplitude from 2.5 A to 0.125 A, with the sample pre-magnetized for 10 cycles before each measurement. The signal frequency was 1 Hz, and the sampling rate was 800 kHz, resulting in 800 000 measured points per channel of the recorded signal.

The obtained magnetic flux waveforms in the sample and in the yoke were compared, and their relationship was evaluated using the Pearson correlation coefficient (r_P). Both the entire waveform (globally) and selected segments (locally) were analyzed. The influence of the air gap on the correlation coefficients was also investigated. The measurements showed that even in the

presence of an air gap, the correlation coefficients remain high, confirming the reliability of the method. The corresponding waveforms at an applied current 2.375 A are shown in Fig. 5.

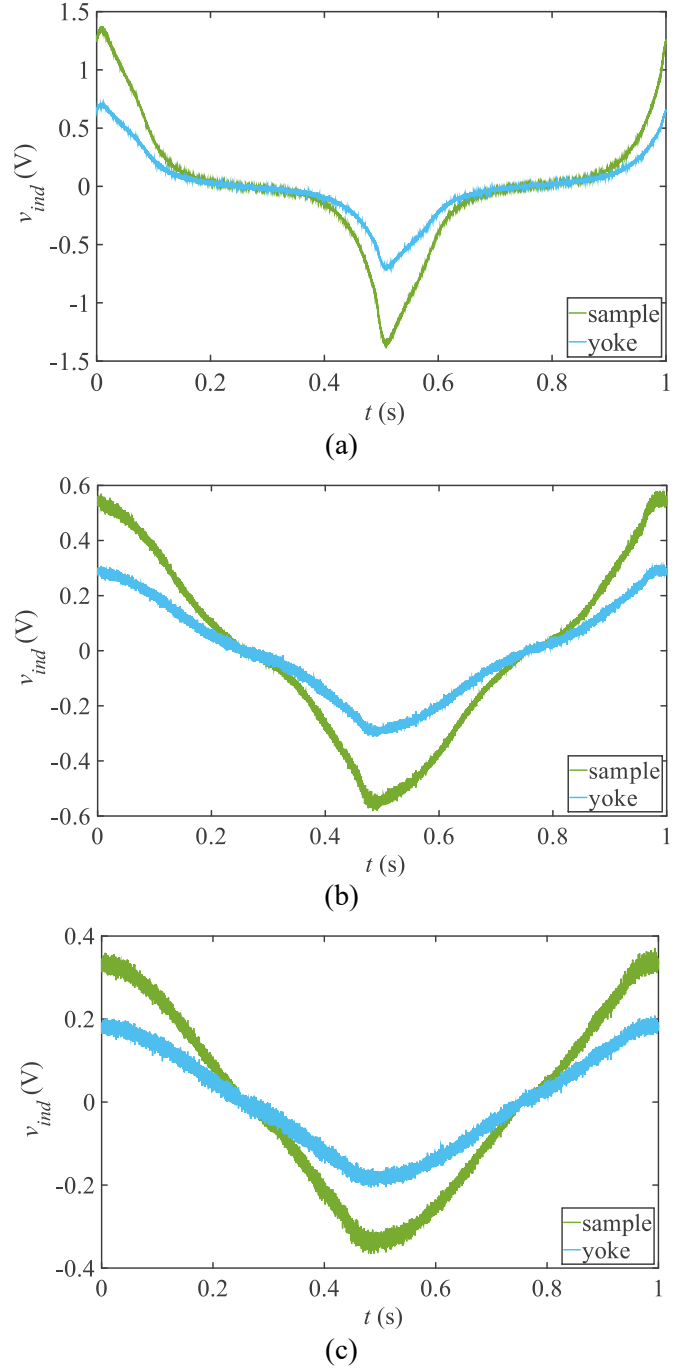


Fig. 5. Induced voltage signals in the sample and the yoke at applied current 2.375 A: (a) air gap 0.0 mm, $r_P = 0.9989$, (b) air gap 0.1, $r_P = 0.9994$, (c) air gap 0.2 mm, $r_P = 0.9993$

Global correlation coefficients were evaluated for all amplitudes and for all considered air gaps. A brief overview is given in Tab. 1. The lowest value of r_p was 0.955, observed at an air gap of 0.2 mm and at the lowest amplitude of 0.125 A. These results indicate that the correlation coefficient slightly decreases with increasing air gap. However, for the investigated air gap thicknesses it remains close to 1, confirming the accuracy and applicability of this measurement method.

Table 1. Global correlation coefficients r_p for each air gap

Air gap	Min	Max	Avg
0.0 mm	0.994079	0.999646	0.999037
0.1 mm	0.973877	0.999482	0.997649
0.2 mm	0.955051	0.999279	0.995626

Local correlation coefficients were also evaluated for all amplitudes at an air gap of 0.0 mm, in the various time intervals ($t = 0$, $t = T/4$, $t = T/2$, $t = 3T/4$, $t = T$). The lowest local value of r_p was 0.894 at $t = 3T/4$ and at an amplitude of 1.875 A. A statistical summary of these values is presented in Tab. 2.

Table 2. Local correlation coefficients r_p in different time intervals, with air gap 0.0 mm

t	Min	Max	Avg
0	0.955526	0.994364	0.982164
$T/4$	0.911433	0.952303	0.932851
$T/2$	0.921413	0.993813	0.974727
$3T/4$	0.894485	0.965684	0.934760
T	0.942076	0.994896	0.980205

These observations confirm a strong correlation between the measured waveforms. The presence of identical local extrema suggests a common origin, most likely associated with Barkhausen noise caused by the pinning of domain walls at inhomogeneities and micro-

scopic defects in the crystal lattice, which further indicates that the magnetic flux in the sample and in the yoke is highly correlated. The correlations were evaluated at several time positions along the waveform, and an illustrative example is shown in Fig. 6, which presents a segment of 500 data points (just after $t = T/4$) from the waveform measured at an excitation current amplitude of 2.375 A and an air gap of 0.0 mm.

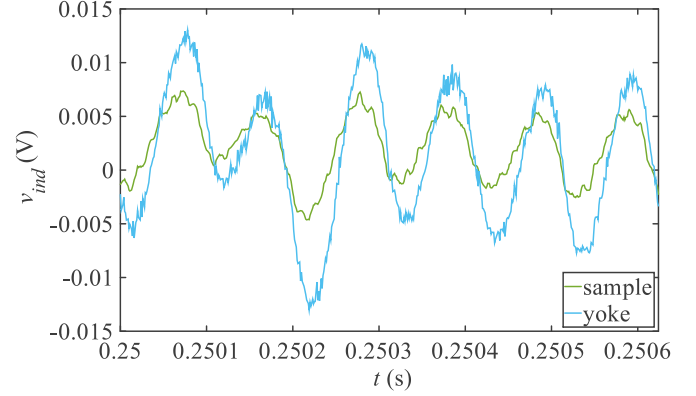


Fig. 6. Induced voltage signals in the sample and in the yoke – zoomed section of the waveform (air gap 0.0 mm, 2.375 A, $r_p = 0.9273$)

Based on the high correlation coefficients, both global and local, and for all investigated air gaps, it can be concluded that the magnetic flux in the sample and in the yoke is sufficiently coupled, despite the expected significant leakage flux in the region of the contact surface between the sample and the yoke.

From a practical point of view, since the calibration of $H(t)$ is problematic and a high correlation between the magnetic flux in the sample and in the yoke has been demonstrated, it is possible to introduce an equivalent to the original $B(H)$ loops in the form of $\Phi(I)$ loops. The dependencies obtained from the measured values at the highest amplitude H_{max} are shown in Fig. 7. It can be observed that the curves are nearly identical, with the differences mainly caused by leakage magnetic flux at the interface between the sample and the yoke. The graphs also illustrate the influence of the air gap, highlighting the importance of minimizing it.

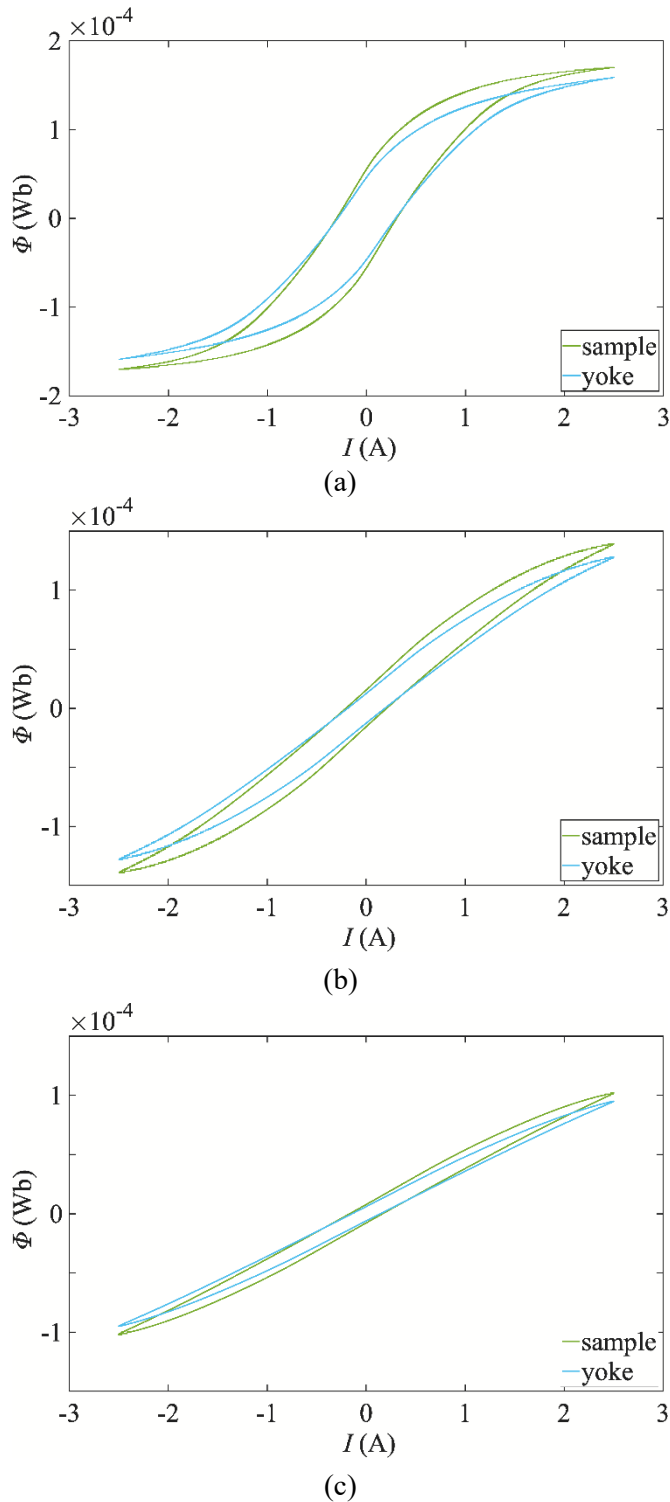


Fig. 7. Magnetic flux as a function of current in the sample and in the C-core, values at maximum amplitude H_{max} : (a) air gap 0.0 mm, (b) air gap 0.1 mm, (c) air gap 0.2 mm

6 Conclusion

The applicability of Magnetic Adaptive Testing (MAT) to magnetically open samples was investigated. The relationship between the magnetizing current and the magnetic field intensity in the sample was experimentally examined using Hall probe measurements at

different positions relative to the sample. The results confirmed that this relationship can be significantly non-linear and may exhibit hysteresis, which complicates the direct calibration of the magnetic field intensity in open magnetic configurations. The MAT method addresses this by normalizing the measured values against an initial baseline, allowing for the tracking of relative changes in the parameters. This approach ensures that most systematic errors effectively cancel out when the data are expressed as ratios of actual-to-initial values.

Furthermore, the relationship between the magnetic flux in the sample and in the yoke was analyzed by comparing the induced voltage measured by sensing coils placed on both elements. The obtained results showed a very high correlation between the magnetic flux waveforms, both globally and locally, for all investigated amplitudes and air gaps. Even in the presence of an air gap, the correlation coefficients remained close to unity, confirming a strong coupling between the magnetic flux in the sample and in the yoke.

These analyses lead to the conclusion that measurements performed on the yoke are sufficient to relatively reliably predict the magnetic behaviour in the sample. This allows the introduction of equivalent $\Phi(I)$ loops instead of conventional $B(H)$ loops, which eliminates the need for precise calibration of the magnetic field intensity. An important implication of this result is that a closed magnetic circuit is not necessary; a suitably shaped C-core is sufficient. When placed on the sample, it enables the magnetic flux waveform in the sample to be determined with high accuracy based on the measured signal. These findings confirm that the MAT method remains reliable and applicable also for magnetically open samples, representing an important step toward further research and practical application of the method.

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