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Nondestructive investigation of wall thinning in ferromagnetic material by Magnetic adaptive testing: influence of yoke size

Nieniszczące badanie przewężenia materiałów ferromagnetycznych za pomocą adaptacyjnych testów magnetycznych: wpływ rozmiaru jarzma

ABSTRACT

Magnetic adaptive testing is a powerful way of nondestructive evaluation. Minor magnetic hysteresis loops are systematically measured and evaluated. In the present work this technique was applied for detection of local thinning of ferromagnetic plates. The same plate with a given artificial slot was tested by different size magnetizing yokes. A definite maximum of magnetic descriptors was found, as a function of yoke size, which made possible the optimization of the yoke size for a given size of defect. The character of the maximum also revealed that the measurement is not sensitive for the geometrical parameters: the same yoke is suitable for detection of defects in a wide range. It was proved by simulation that the change of the magnetic flux density in the yoke – due to local thinning – was responsible for the observed effect. Good correlation was found between simulation and experimental data. The result of this work will help to find the optimal parameters of the experimental arrangement.

Keywords: *electromagnetic nondestructive testing, wall thinning, magnetic hysteresis measurements, magnetic adaptive testing, magnetic field simulation*

STRESZCZENIE

Magnetyczne testy adaptacyjne są skutecznym sposobem oceny nieniszczącej. W ich trakcie mniejszościowe pętle histerezy magnetycznej są systematycznie mierzone i oceniane. W niniejszej pracy zastosowano tę technikę do wykrywania miejscowego przewężenia płytek ferromagnetycznych. Ta sama płyta ze sztucznymi defektami została zbadana przy wykorzystaniu jarzma magnetyzującego o różnych rozmiarach. Określono maksymalną liczbę deskryptorów magnetycznych, zależnych od wielkości jarzma, co umożliwiło optymalizację rozmiaru jarzma dla danej wielkości defektu. Uzyskana charakterystyka ujawniła również brak wrażliwości wyników pomiaru na parametry geometryczne: to samo jarzmo nadaje się do wykrywania defektów w szerokim zakresie. Udowodniono, że za obserwowany efekt odpowiedzialna była zmiana gęstości strumienia magnetycznego w jarzmie - będąca wynikiem lokalnego przerzedzania. Stwierdzono dobrą korelację między symulacją a danymi eksperymentalnymi. Uzyskane wyniki umożliwią wyznaczenie optymalnych parametrów układu pomiarowego.

Słowa kluczowe: *elektromagnetyczne badania nieniszczące, przewężenie materiału, pomiary histerezy magnetycznej, magnetyczne testy adaptacyjne, symulacja pola magnetycznego*

1. Introduction

For pipes used in industry, wall thinning is one of the most serious defects [1, 2]. Local wall thinning on the inner surface of a pipe may occur due to the stream of coolant flowing inside the pipe, causing a serious problem of maintenance of the piping systems. The inspection should be done from the outer side of the pipe. Recently many nondestructive testing techniques have been used for the measurement of pipe wall thinning. Currently the magnetic flux leakage (MFL) method is the most commonly used pipeline inspection technique [3,4]. Another technique, the recently developed nondestructive magnetic method (Magnetic Adaptive Testing, MAT [5]) was also successfully applied for the inspection of wall thinning in layered ferromagnetic materials. MAT is based on systematic measurement of minor magnetic hysteresis loops and introduces a large number of magnetic descriptors to diverse variations in nonmagnetic properties of ferromagnetic materials, from which those, optimally adapted to the just investigated property and material, can be picked up. It was shown in [6] that Magnetic Adaptive Testing was an effective and promising tool for nondestructive detection of local thinning of a plate from the other side of the specimen. The method gave good results also in a layered ferromagnetic material. It was proved by these model experiments, that a 9 mm wide and 2 mm deep slot, made in a 3 mm thick ferromagnetic material could be well detected with good signal/noise ratio through one (or even two) air-gap(s) and through 3-6 mm additional ferromagnetic material. The slot is seen not only in case when the measuring yoke is positioned exactly above it, but from about ±10 mm distance, too, with an acceptable signal/noise ratio.

To improve the applicability of MAT, the measurement conditions should be optimized. On one side it is important to study, how the modification of the measured hysteresis loops, caused by the presence of an artificial slot in the investigated ferromagnetic plate are influenced by the geometry of the applied magnetizing yoke. For this purpose

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DOI: 10.26357/BNiD.2018.012

numerical simulation was performed. In our recent work [7] we calculated how the geometrical parameters of the measured arrangement affect the change of the magnetic flux inside the magnetizing yoke, which is the main source of the detected change in the measured signal. The yoke size and influence of air gap (which is extremely important in open magnetic circuits) were also taken into account in a three plate system of ferromagnetic plates. The result of simulation will help to find the optimal parameters of the experimental arrangement. On the other side it is also important to determine, how the real measured magnetic parameters depend on the size of the applied magnetizing yoke. The purpose of the present work is to study – both by simulation and by experiments – the influence of the size of magnetizing yoke on the magnetic parameters, in case of detection of an artificial slot in a ferromagnetic plate. The results of simulation and measurement are compared with each other as well.

2. Experimental arrangement

A 500 mm x 300 mm x 6 mm size carbon steel plate was chosen for the measurement, which contained a 10 mm x 1 mm size slot in the middle of the plate along the whole plate. The magnetizing yoke was moved over the top surface of the sample, while slot was located in the bottom side, as shown in Fig. 1.

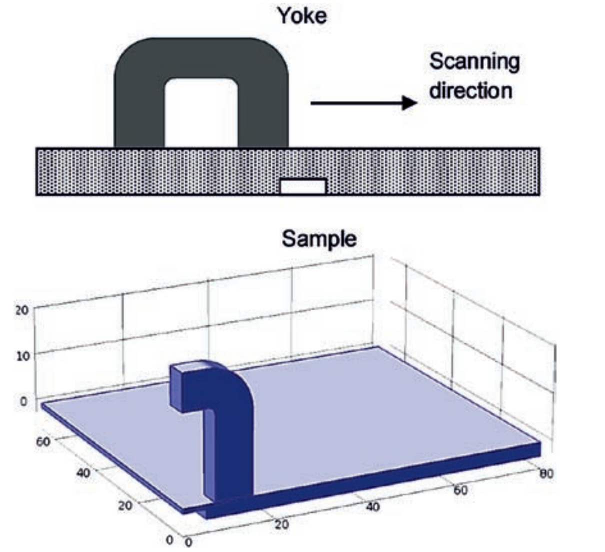


Fig. 1. Configuration used both for measurement and simulation. The geometry down represents a quarter-view of the arrangement, showing only part of the whole plate, and with the yoke in central position right above the slot.
Rys. 1. Konfiguracja używana zarówno do pomiarów, jak i symulacji. Geometria po prawej stronie przedstawia ćwiartkę układu, pokazując tylko część całej płyty, a także jarzmo w pozycji centralnej tuż nad szczeliną.

Tab. 1. Magnetizing yokes used for measurements and the distance between their legs.
Tab. 1. Odległości pomiędzy kolumnami jarzm magnesujących wykorzystanych podczas pomiarów.

Yoke No.	1	2	3	4	5	6
Distance between yoke legs (mm)	8	11	14	19	25	30

Different size of yokes were used. The yokes were C-shaped laminated Fe-Si transformer cores. The distance between the legs of the yokes are given in Table 1.

3. Numerical simulation

The AC/DC Module of the Comsol Multiphysics® finite element software was used for the simulations [8]. The physics setting is "magnetic fields" (mf), the governing equation of which is

$$\nabla \times \left(\mu^{-1} \nabla \times \vec{A}\right) = \vec{J}. \tag{1}$$

Here $\vec{A}$) is the magnetic vector potential, from which the magnetic flux density can be obtained as $\vec{B} = \nabla \times \vec{A}$, $\vec{J}$ is the current density, and μ stands for the local permeability of the media. Note that in this study one is allowed to use linear material model of both the yoke and the plate, for which we assumed $\mu = 5000\mu_0$. The excitation is prescribed as a surface current density $\vec{K}$ on the lateral surfaces of the "bridge" of the yoke, which adds up to a total current of 1 A. The flux through the yoke is computed by an integral of the flux density over the cross-sectional surface, S, of the yoke:

$$\Phi = \int_S \vec{B} \cdot \overrightarrow{ds} \tag{2}$$

The variation of magnetic flux, Φ_1 and Φ_2 was calculated according to the above described way. Let Φ_1 denote the flux in the yoke according to (2) when there is no slot in the material ($\mu_r = 5000$) and, in turn, Φ_2 be the flux in the presence of the slot ($\mu_r = 1$). We define the relative change of the magnetic flux as $|\Phi_1 - \Phi_2|/\Phi_1$. By the simulations we investigated how this flux change depends on the distance between the legs of the magnetizing yoke.

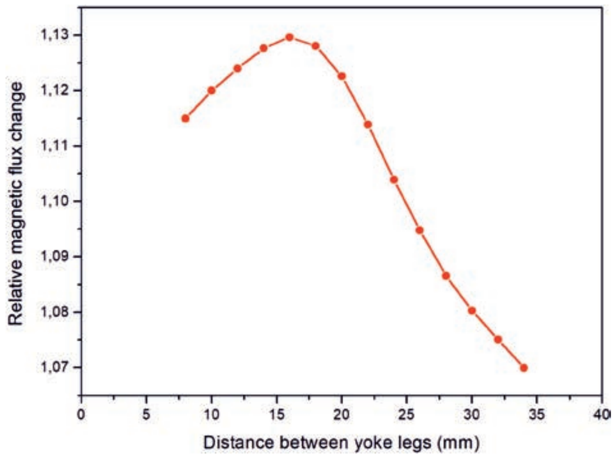
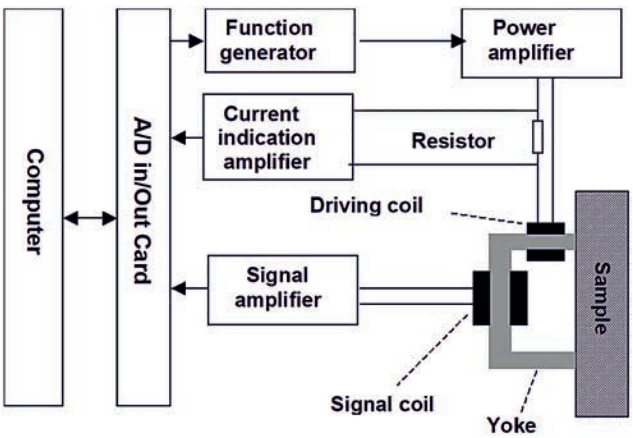


Fig. 2. Relative flux change $|\Phi_1 - \Phi_2|/\Phi_1$ in the yoke, as a function of the yoke leg distance.
Rys. 2. Względna zmiana strumienia $|\Phi_1 - \Phi_2|/\Phi_1$ w jarzmie, w zależności od odległości kolumny jarzma.

In Fig.2. the calculated flux change is plotted as a function of the distance between the legs of the magnetizing yoke. The Figure shows how the relative change of the flux, $|\Phi_1 - \Phi_2|/\Phi_1$ depends on the distance between the yoke legs. It can be seen that by optimal choice of the yoke, the obtained flux change can be maximized. As expected, the flux change depends on the dimensions of the magnetizing yoke (e.g. distance between yoke legs). The presence of the slot results close to 13% modification in the relative magnetic flux change if the size of yoke is optimized to the size of slot. However, no drastic change is observed around the top area if the yoke size is modified by ±5 mm range.

4. Magnetic adaptive testing

MAT investigates a complex set of minor hysteresis loops (from a minimum amplitude of the magnetizing field, with increasing amplitude by regular steps) for each position of the magnetizing yoke. A specially designed Permeameter [9] with a magnetizing yoke was applied for measurement of families of minor loops of the magnetic circuit differential permeability. The samples were magnetized by the attached yoke, having a magnetizing and a pick-up coil, wound on the legs of the yoke. The magnetizing coil gets a triangular waveform current with step-wise increasing amplitudes and with a fixed slope magnitude in all the triangles. Block-scheme of the Permeameter and triangular variation of the magnetizing current with time are illustrated in Fig. 3.



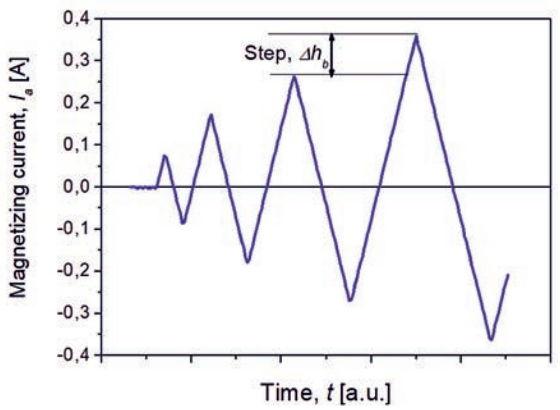


Fig. 3. Block-scheme of the Permeameter (up) and triangular variation of the magnetizing current with time (down).

Rys. 3. Schemat blokowy miernika przenikalności magnetycznej (góra) i przebieg trójkątny prądu magnesującego w czasie (dół).

This produces a triangular time-variation of the effective field in the magnetizing circuit and a signal is induced in the pick-up coil. As long as the field sweeps linearly with time, the voltage signal in the pick-up coil is proportional to the effective permeability of the magnetic circuit. The permeameter works under full control of a PC computer, which registers data files for each measured family of the minor "permeability loops".

The experimental raw data are processed by an evaluation program, which divides the originally continuous signal of each measured sample into a family of individual permeability half-loops. The program filters experimental noise and interpolates the experimental data into a regular square grid of elements, $\mu \equiv \mu(h_a,h_b)$, of a μ-matrix with a pre-selected field-step. Degradation functions, created straight from the induced signal (which is proportional to the average permeability measured in the magnetic circuit "measuring head – measured plate"), are labeled as the μ-degradation functions. Coordinates h_a, h_b of the elements represent the actual magnetic field value, h_a, on the actual minor loop with amplitude h_b. Each μ-element represents one "MAT-descriptor" of the investigated sample. The matrices are processed by another evaluation program, which divides values of their elements by corresponding element values of a chosen reference matrix (i.e. matrix standardization), and arranges each set of the mutually corresponding elements μ of all the evaluated μ-matrices into a μ(x)-degradation function. In general x can be any independently measured parameter. In our case this is the position of the center of the magnetizing yoke with respect to the axis of the slot when it moves step-by-step on the surface of the sample along a straight line perpendicular to the length of the slot. The slot is located on the bottom side and the axis of the yoke is oriented perpendicular to the axis of the slot. The details of experimental apparatus and evaluation (i.e. how the optimal MAT descriptors are chosen) are presented in [10]. In some cases, the degradation functions based on the derivative of permeability with respect to the field, h_a, $\mu' = d\mu/dh_a$ are more sensitive. They are referred to as the μ′-degradation functions.

Once the degradation functions are computed, the next task is to find the optimum degradation function(s) for the most sensitive and enough robust description of the investigated material degradation. The matrix-evaluation program calculates also sensitivity of each permeability μ(x)-degradation function and draws their "sensitivity map" in the plane of the field coordinates (h_a,h_b). A 3D-plot of sensitivity of the degradation functions can substantially help to choose the optimum one(s). This map shows relative sensitivity of each μ(x)-degradation function with respect to the independently measured x-parameter of the investigated material. Sensitivity of each degradation function is computed as the slope of its linear regression and it is expressed by a color and/or shade in the sensitivity map figure. This map is very useful if we want to characterize the reliability and reproducibility of the MAT descriptors. The sensitivity map gives useful information about the relative change of the investigated magnetic descriptor with respect to the independent variable (the top of the "hills" are those area(s) from where the most sensitive MAT-degradation functions can be taken). On the other side it also indicates, how reliably the parameter can be determined if the measurement is repeated (large plateaus are favourable from this point of view, where parameters depend only very slightly from the actual choice of the exact field coordinates values h_a and h_b). In this measurement it is difficult to determine exact values of the magnetic field, h, inside the sample, due to the open magnetic circuit. Because of this the magnetizing current, I, (given in A) is used to characterize the samples' magnetization when MAT descriptors are evaluated.

5. Experimental results

The results of the measurements performed on the investigated plate containing the artificial slot are given in Fig. 4. Here the results of line scans are presented: different yokes (as shown in Table 1) were scanned over the surface in 5 mm steps along a line perpendicular to the direction of the slot. In all cases MAT degradation functions are normalized by the corresponding degradation function measured at the largest distance (−40 mm) from the centre of the slot, so the points in Fig. 4 represent the relative change of the magnetic parameter with respect to the „no slot" case. In the present case the derivative $d\mu/dI = \mu'$ was found as the most sensitive descriptor and therefore in the whole work the μ'-degradation functions are used. It is seen that in the most favourable case 100% modification of magnetic parameters was experienced caused by the presence of the slot.

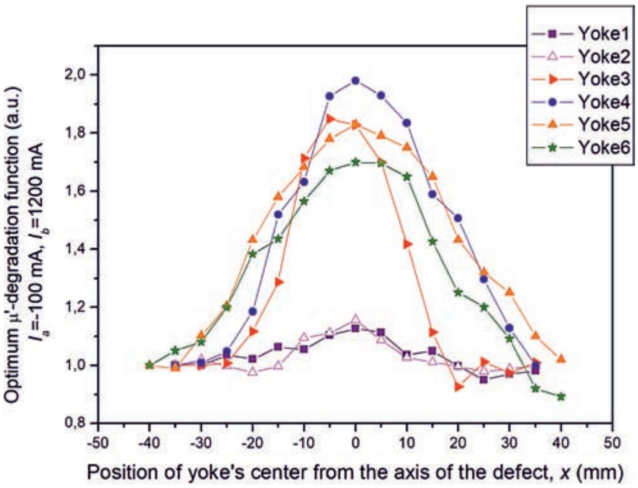


Fig. 4. The most sensitive μ' degradation functions, measured by different yokes, moving the yoke along the surface of the sample over the defect (defect's center is at x=0).
Rys. 4. Najbardziej czułe funkcje degradacji μ', mierzone przez różne jarzma, podczas przesuwania jarzma wzdłuż powierzchni próbki ponad defektem (środek defektu ma wartość x = 0).

The map of relative sensitivity of the μ'(x)-degradation functions in the case of yoke 4 is shown in Fig. 5. It is also indicated in this figure by crossing lines, from which point the "optimum MAT degradation function" of Fig. 4 is taken.

The maximal values of normalized MAT descriptors (which can be measured at x=0 position, see Fig. 4) are shown in Fig. 6 as a function of the size of magnetizing yoke. This curve is suitable on one side to determine the influence of the yoke size on the values of detectable MAT descriptors for the given arrangement, and on other side to make a comparison between simulated and calculated parameters.

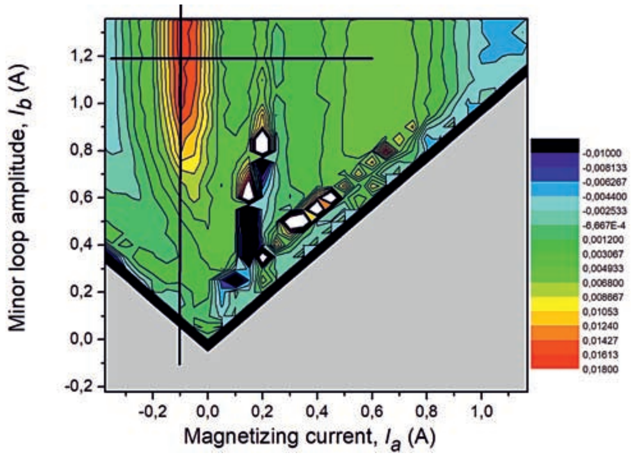


Fig. 5. Sensitivity map of the μ' degradation functions (measured by yoke 4). The degradation functions with the magnetizing current coordinates around I_a=−0.1 A, and with minor loop amplitudes larger than I_b =1 A have the top sensitivity, and is used in Fig. 4.
Rys. 5. Mapa czułości funkcji degradacji μ' (mierzona jarzmem 4). Funkcja degradacji z parametrami prądu magnesującego ok. I_a = -0,1 A oraz z amplitudami mniejszościowych pętli większymi niż I_b = 1 A ma najwyższą czułość i jest wykorzystywana na rysunku 4.

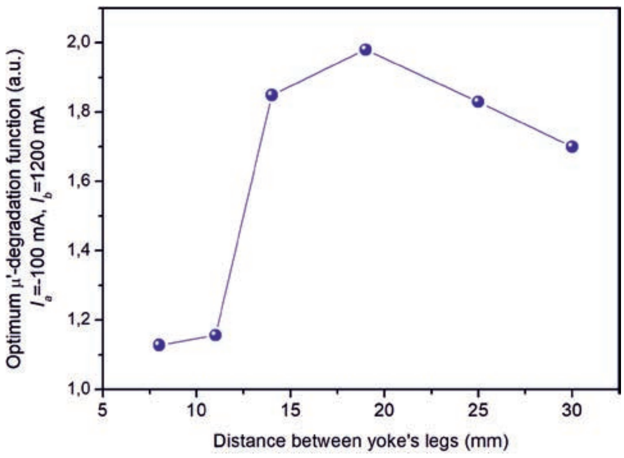


Fig. 6. The maximal values of normalized optimum MAT descriptors as a function of the distance between yoke legs.
Rys. 6. Maksymalne wartości znormalizowanych optymalnych deskryptorów MAT jako funkcji odległości między kolumnami jarzma.

6. Discussion

It was determined empirically that the value of MAT descriptors depend on the size of the magnetizing yoke, if measurements are performed on a ferromagnetic plate having an artificial slot on the bottom side. A definite, well measurable local maximum was found at 20 mm distance between the legs of the yoke. This shows that the geometry of the measurement arrangement (size of magnetizing yoke) can be optimized for a given size of defect. In this particular case a 10 mm wide slot can be detected the most effectively by a yoke having about 20 mm distance between the legs. This result concerns for the investigated case, where one model of the plate was applied with one definite size of defect. However, it is very probable that the observed correlation, that different size defects need different size yokes can be more general. It is assumed that this tendency is valid for other cases, too, but for a definite and reliable answer to this question more efforts should be done.

The relatively flat curve around the optimal size of the yoke (see Fig. 6) is promising from that point of view, that the sensitivity of the detection of the slot is not influenced much (at least in a certain range) on actual choice of the magnetizing yoke's size.

Results of simulations gave similar correlation between the modification of magnetic flux in the yoke (due to defect) and size of yoke. It is worth of mentioning that the optimal size of yoke is more or less the same in empirical case and in simulation. This fact gives on one side a rather promising theoretical background for this type of nondestructive evaluation, and on the other side it means the empirical validation of the simulation.

7. Acknowledgement

The work was supported by the Hungarian Scientific Research Fund (project K 111662).

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