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Nondestructive Detection of Local Material Thinning in Ferromagnetic Materials by Magnetic Adaptive Testing

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ABSTRACT

A recently developed nondestructive method, called Magnetic Adaptive Testing, which is based on systematic measurement and evaluation of minor magnetic hysteresis loops was applied for detection of local material thinning in a thick, L-shaped ferromagnetic carbon steel, which simulates T-tubes with reinforcing plates. Artificially made slots were reliably detected with a good signal/noise ratio from the other side of the specimen, even through a covering ferromagnetic plate.

KEYWORDS

Wall thinning, Magnetic nondestructive testing, Magnetic Adaptive Testing, Magnetic hysteresis

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1. Introduction

Local material/wall thinning is one of the most frequent and serious defects of pipes and other construction elements used in industry [1,2]. Its timely detection and evaluation is very important for prediction of lifetime of the pipes in order to avoid severe accidents. As a rule, the inspection is required to be done from the outer side of the pipeline. In Japan there is a special concern about local wall thinnings at locations under reinforcement shields that cover outside of the pipe at positions where a branch pipe is connected to the main one. Because the reinforcement shield and the pipe wall form two layers of metal, it is difficult to inspect the inside surface of the pipe under the reinforcement shield by ultrasonic thickness gauge. The pulsed eddy current testing technology was developed in recent years to detect the wall thinning [3-5]. Because of its rich frequency components and applicability of a large electric current, the pulsed eddy current method shows promising capability in detection and evaluation the defects in deep regions of non-magnetic conducting materials.

However, it is difficult to apply eddy current methods in thick *ferromagnetic* plates. For ferromagnetic materials the magnetic flux leakage (MFL) method was discussed, and size of a slit fabricated on the under-layer of a layered specimen was estimated from the flux leakage profile [6-8].

The recently developed method of Magnetic Adaptive Testing (MAT) [9,10] proved to be another candidate for the inspection of wall thinning in layered ferromagnetic materials. MAT introduces a large number of magnetic descriptors to diverse variations of structural and shape properties of ferromagnetic materials, from which those, optimally adapted to the just investigated property and material, can be picked up. It was shown in [11] that Magnetic Adaptive Testing was an effective and promising tool for nondestructive detection of local thinning of a steel plate from the other side of the specimen. The method gave good results also in layered ferromagnetic plates. It was proved by these model experiments, that a 9x2 mm^2 slot, made in a 3 mm thick ferromagnetic material could be well detected with a good signal/noise ratio through one (or two) air-gap(s) and through 3-6 mm additional ferromagnetic material. The slot was seen not only in case when the

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measuring yoke was positioned exactly above it, but from about ±10 mm distance, too, with a still acceptable signal/noise ratio.

It has been also recently shown [12] that MAT can be used for inspection of wall thinning in thick, layered carbon steel tube specimen, which simulates the T-tubes with a reinforcing plate in nuclear power plants. The existence of an artificial slot was detected with a good signal/noise ratio and with a good reliability even under a reinforcement shield that covered outside of the pipe.

The purpose of the present work is to demonstrate the capability of MAT technology for detection and evaluation of local wall thinning in T-tubes with reinforcing plates. For the purpose, we fabricated several L-shaped samples with various slots, which simulate T-tubes with reinforcing plates, and the signals are discussed in view of detectability and measurement reliability. In the present work we investigate a series of identical samples with different sizes of artificial slots, in contrast to [12], where only one single specimen was available with a given size artificial slot. So, not only the geometry of the sample is different in this work, but we will get information about the influence of the slots' depth on the measured signal and on the evaluated MAT parameters. We try to determine the detectable smallest slot in the given configuration. We investigate also – in contrast to [12] – how the detected signal decreases as a function of measuring head position from the slot. Additionally, it will be also shown, what is the difference in the calculated MAT parameters if the μ-degradation function (permeability) and μ'-degradation function (first derivative of permeability) are used.

2. Magnetic Adaptive Testing

Magnetic Adaptive Testing is based on systematic measurement and evaluation of minor magnetic hysteresis loops. For this purpose a specially designed Permeameter [13] with a magnetizing/sensing yoke is applied for measurement of families of minor loops of the magnetic circuit differential permeability. The block-scheme of the device and the sketch of the yoke can be seen in Fig. 1.

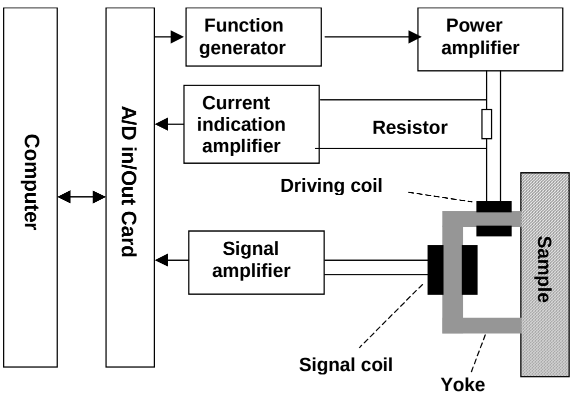

Fig. 1: Block-scheme of the Permeameter and sketch of the yoke

The magnetizing coil wound on the yoke gets a triangular waveform current with step-wise increasing amplitudes and with a fixed slope magnitude in all the triangles. The voltage signal in the pick-up coil is proportional to the differential permeability of the magnetic circuit. The Permeameter works under full control of a PC computer, which sends the steering information to the function generator, and collects the measured data. An input-output data acquisition card accomplishes the measurement. The computer registers data-files for each measured family of the minor permeability loops. They contain detailed information about all the pre-selected parameters of the voltage signal induced in the pick-up coil. Before each measurement the sample is demagnetized by a triangular waveform decreasing current. The raw data, which is registered for each sample characterized by a degradation parameter, ε_k, is a family of permeability loops, which is then processed by a special data-evaluation program. The program filters the experimental noise and interpolates the data into a regular square grid of elements, $\mu_{ij}\equiv\mu(F_i,A_j,\varepsilon_k)$, of a μ-matrix with a pre-selected magnetizing field step $\Delta F = \Delta A$. Here A_j is the field amplitude of the j-th minor loop and F_i is the current field value within that minor loop. The consecutive series of $\mu(\varepsilon_k)$-matrices, each taken for one sample with a value of the independent variable, ε_k, describes the magnetic reflection of the material degradation, ε, see [9]. The matrices are processed by a matrix-evaluation program, which normalizes them by the matrix of a reference sample ($\varepsilon = \varepsilon_0$), chosen as the reference matrix, and arranges all the mutually corresponding elements, $\mu_{ij}(\varepsilon_k)$, of all the evaluated $\mu(\varepsilon_k)$-matrices into a table. Each $\mu_{ij}(\varepsilon)$-column of the table numerically represents dependence of one μ_{ij}-matrix element on the independent variable of the material degradation, ε. The dependence is referred to as the *$\mu_{ij}(\varepsilon)$-degradation function*. The most sensitive of all the degradation functions is found with the help of a *map of sensitivity* (see [10] for details) and it is then used for highly sensitive characterization of structural and shape modifications of the investigated material.

The paragraph above describes the method of MAT as it is used for determination of the most sensitive characterization (i.e. of the most sensitive degradation function) of variation of the material properties of *different samples*, typically referred to as the “material degradation”. In the case of the investigation of local thinning of a *single plate* of ferromagnetic material, shown below, the single plate is *scanned* by the magnetizing/sensing yoke in a sequence of pre-determined *positions*, x_k, of the yoke on the surface of the plate. In this case the magnetic behaviour of the sample is modified not due to the structural changes in the sample, but due to the modified distribution of magnetic flux inside the material, close to the reduced magnetic cross section (wall thinning). As a result, difference can be detected in MAT parameters. Measurement at each position, x_k, is then characterized by one $\mu(x_k)$-matrix, and similarly as in the above paragraph $\mu_{ij}(x)$-degradation functions are constructed. Then, the most sensitive of all the $\mu_{ij}(x)$-degradation functions is found and used for highly sensitive determination of the yoke position, x_D, under which the local thinning of the plate (i.e. the defect) is situated. The position, x_0, of the yoke, under which there is no defect, and which is far from the plate boarders, is used for normalization.

The optimal degradation functions are chosen by a simple special program of sensitivity maps. The degradation functions can be constructed either directly from the signal data (μ-degradation functions), or alternatively from the first derivative of the data with respect to the magnetizing field (μ’-degradation functions), or from any other derivate or integral of the measured signal. The information content is never increased by differentiation or integration of the signal data, however, some features can become more distinctive or more convenient. In the following, we present and use μ-degradation functions and μ’-degradation functions (and their reciprocal values) as obtained from measurement of the investigated samples.

3. Samples

Three L-shaped, flat samples, which simulate the T-joints with reinforcing plates were measured. Both the geometry of the samples and a photo of one of them are given in Figs. 2 and 3.

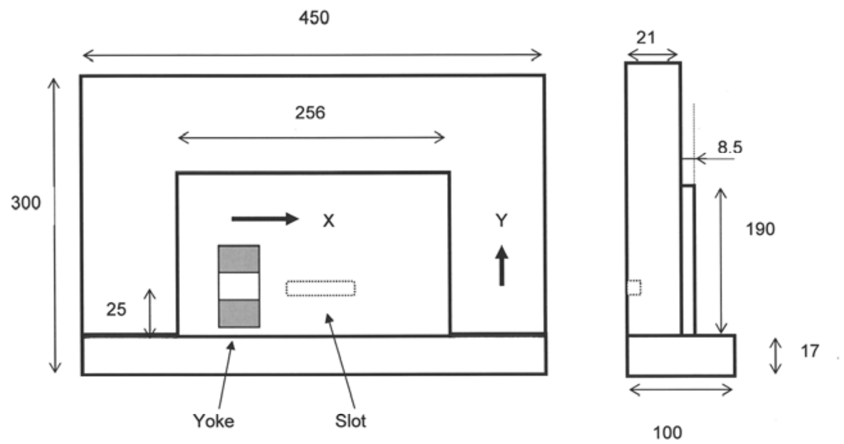

Fig. 2. Sketch of the measured L-shaped carbon steel sample. Values are given in mm

The samples were made of a carbon steel. An artificial slot was fabricated in the bottom of each sample. Each slot was located under a 8.5 mm thick additional ferromagnetic plate, which was welded to the sample. The samples were identical, but for depths of the slots. The length and width of the race-track shape slots were 50x20 mm^2 in all the samples, but their depth was different: 10.3 mm, 5.2 mm and 2.1 mm, respectively.

4. Measurement and results

Measurement of the permeability loops was performed by scanning the magnetizing/sensing yoke over the sample's top surface, i.e. at the opposite side from the slot. The yoke was a C-shaped laminated Fe-Si transformer core. The legs of the yoke were 19x16 mm^2, the distance between the legs was 30 mm. A magnetizing coil (105 turns) and a pick-up coil (35 turns) were wound on the legs of the yoke.

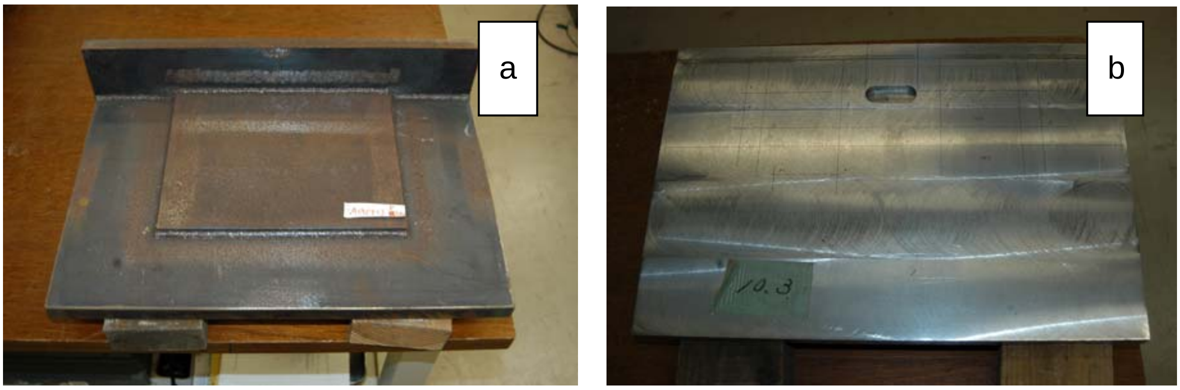

Fig. 3. Photo of the measured L-shaped carbon steel sample. a) top side with the reinforcement shield, b) bottom side with the artificial slot

The signals of the pick up-coil for four different cases are shown in Fig. 4. In the first three cases the three different samples (with different depths of the slot) were measured, while the yoke was positioned above the slot. In the fourth case („no slot“) the yoke was moved as far from the slot as was possible on the given sample. The modification of the shape of the permeability loops, due to the existence of the slot under the magnetizing yoke is seen very well.

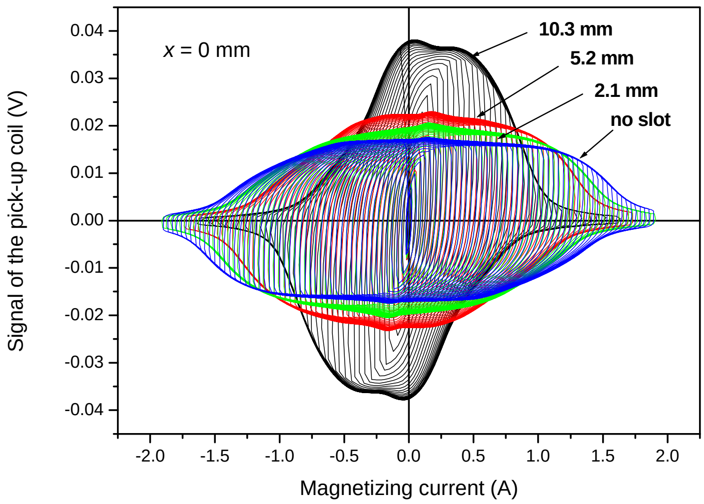

Fig. 4. Examples of families of the permeability loops vs. magnetizing current, measured at the three different slots and without the slot.

The measurements on the different samples were performed in such a way, that the yoke was moved by 10 mm steps along the sample's surface (along the X-direction), as indicated in Fig. 2 by the arrow, and the series of permeability loops were measured at each position. The MAT parameters were evaluated as functions of the yoke position. The yoke position, x, was determined with respect to the center of the yoke. At position $x = 0$ mm the center of the yoke was exactly above the center of the slot. The distance of the yoke from the longitudinal slot axis (along the direction Y in Fig. 2) is indicated by y. The axis of the slot is located at $y = 0$ mm. The center of the yoke moves in the X-direction exactly above the slot, if $y = 0$ mm.

MAT degradation functions were evaluated as functions of the yoke position along X-direction. Each MAT degradation function is normalized by the corresponding one, which belongs to the $x = -70$ mm position (the most distant from the slot). A μ-degradation function is shown in Fig. 5 as a function of the yoke's position in the case of the sample with the 10.3 mm deep slot. About 20% modulation of the μ-degradation function is observed due to the existence of the slot on the bottom of the sample. The slot can be reliably detected. (The error bars in the figure mean the scatter of the points if repeated measurements are averaged.)

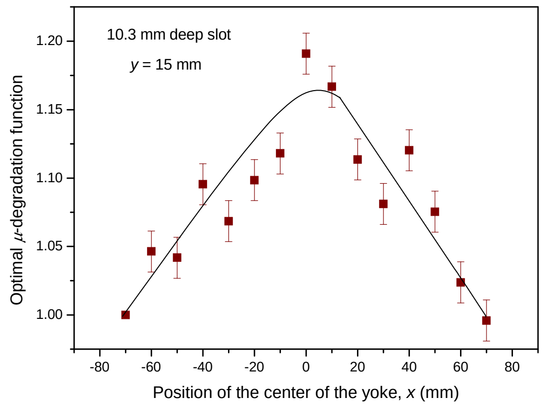

Fig. 5. The optimal μ-degradation function as obtained by scanning of the magnetizing yoke along the surface of the sample (with 10.3 mm deep slot) at y = 15 mm distance from the axis of the slot.

Even more sensitive results were obtained when the $\mu'(x)$-degradation functions (actually their reciprocal values) were considered. These $1/\mu'(x)$-degradation functions are further on referred to as the "Optimal $1/\mu'(x)$-degradation functions". Instead of the 20% modulation of the $\mu(x)$-parameters due to existence of the 10.3 mm slot, about 300% modulation can be detected by use of the $1/\mu'(x)$-degradation functions. The influence of the slot was systematically investigated and the dependence of $1/\mu'(x)$-degradation functions on the yoke's position is shown below.

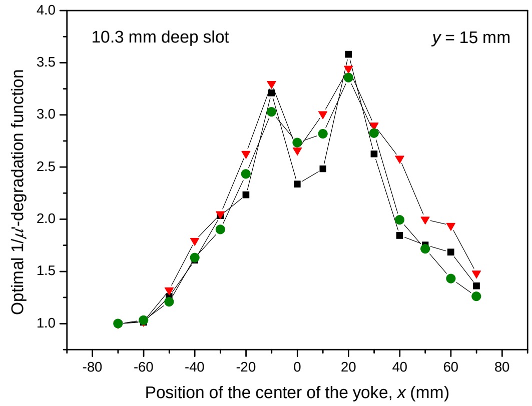

Fig. 6. Reproducibility of the measurement: three repeated scans on sample having 10.3 mm deep slot. The magnetizing yoke was scanned along the X-direction while keeping y = 15 mm.

Reproducibility of the performed measurement was checked on the sample with the 10.3 mm deep slot: Three repeated scans on this sample were performed. The magnetizing yoke was scanned along the X-direction while keeping y = 15 mm. The result of the measurements is shown in Fig. 6.

Measurements were also repeated at different y distances from the axis of the yoke on the sample with the 10.3 mm deep slot. The optimally chosen, normalized MAT parameters as functions of the distance from the center of the slot are shown in Fig. 7, for five different y values. It is seen, that even if the yoke is moved 45 mm far from the axis of the slot, the slot can be still reasonably detected. No change of the MAT parameters can be seen very far from the slot (close to the boundary of the reinforcement shield). This is also an important result, because – due to the complicated shape of the specimen, at least in principle – the measured permeability loops can be modified by the edge of the ferromagnetic plate.

The optimal $1/\mu'(x)$-degradation functions are shown in Fig. 8, for all the three samples with differently deep slots (at y = 0).

No surprise, the lowest sensitivity was recorded with the shallowest slot (2.1 mm deep slot in the 21 mm thick plate under the 8.5 mm cover). However, even in this case about 50% difference was observed, which is still enough for any reliable detection of the slot. The enlarged result of the measurement, performed on 2.1 mm slot sample is shown in Fig. 8 as an insert. This result proves that even a 7% deep slot (compared with the total thickness of the plate and the cover) can be still reasonably detected in the tested materials.

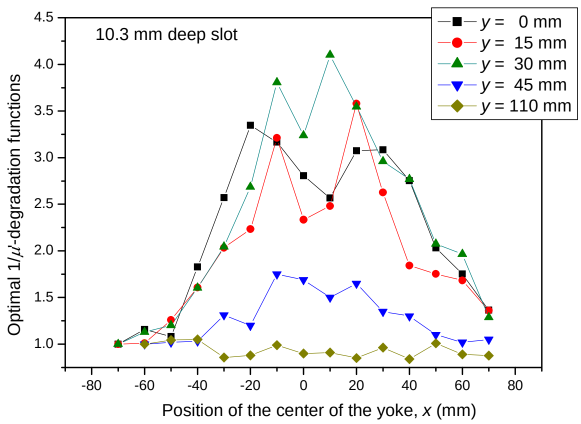

Fig. 7. Optimally chosen $1/\mu'(x)$-degradation functions as obtained by scanning the magnetizing yoke along the surface of the sample (with 10.3 mm deep slot) at different distances from the axis of the slot.

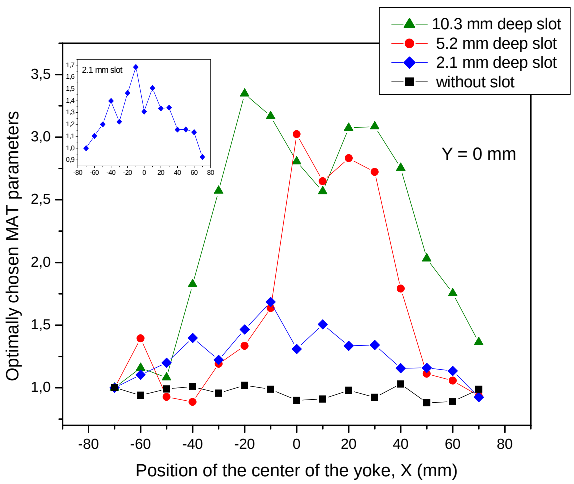

Fig. 8. Optimally chosen $1/\mu'(x)$-degradation functions as obtained by scanning the magnetizing yoke along the surface of the samples with 10.3, 5.2 and 2.1 mm deep slots, and without slot.

5. Discussion

The main intention of the present measurement was *to show principal applicability* and *to estimate possible sensitivity* of the MAT method for indication, and/or for quantitative appraisal of ferromagnetic wall thinning, if detected through a reinforcing ferromagnetic shield, close to a T-shaped branching of pipelines. For this simple purpose we worked with a single magnetizing/sensing yoke, the dimensions of which were chosen as to be of a similar order as the dimensions and thickness of the investigated plates and of the testing artificial slots. The experiment was successful, but evidently, for purposes of practical application, it can be only expedient to advance the performance by detailed optimization of the dimensions, shape and windings of the yoke, taking into consideration the actual object to be tested. Simple computations with the aid of finite elements method will be probably ideal for the optimal concrete applications, but the presented experiment with the yoke dimensions roughly fitting order of the relevant dimensions of the investigated object can certainly give a good starting point.

It is sure that the local minimum of $1/\mu'(x)$-degradation functions, close to $x = 0$, is not an experimental error. It was systematically experienced in all cases, and very similar local minimum of $1/\mu'(x)$-degradation functions, close to the center of the artificially made slot, was also observed in a carbon steel, T-shape tube with reinforcing plate [12]. For giving an exact answer to this question, further investigations are necessary and the simulation of distribution of magnetic flux would be also necessary. This work will be the subject of our future efforts.

At each investigated position of the yoke, differential permeability of a magnetic circuit is recorded, which is composed of the yoke itself and of the section of the investigated material under it. We should not forget, however, that also the “yoke-plate-contact-faces” contribute to the magnetic circuit. The experience showed, that no matter how well the contact faces are polished, the magnetic contact quality fluctuates from one yoke position to another one. This brings about fluctuation of the recorded differential permeability signal, and it is the principal source of the experimental scatter as observed in the figures 5 to 8. As shown in [14], the signal fluctuation can be substantially suppressed by the use of thin non-magnetic spacers glued at contact faces of the yoke legs. Presence of non-magnetic spacers decreases fluctuation of the signal, but at the same time also decreases the signal itself. An optimum thickness of the spacers is usually determined by a trial-and-error method. Thickness of the spacers about 0.1 mm can be recommended as the starting point. For the rough informative experiment of this paper no spacers were applied.

For the sake of simplicity, the coordinates (F_i, A_j) are spoken about as of *magnetic field* coordinates in Section 2. However, it is more practical to measure/read them in the units of the *magnetizing current*. This simplifies the measurement substantially. In particular, as soon as the non-magnetic spacers balance the magnetic contact quality fluctuation, we can characterize the magnetic field values by the magnetizing current values almost with the same straightforwardness as in closed, magnetically uniform circuits (e.g. in continuous rings).

Sensitivity maps of the complex MAT measurements (not explicitly presented in this paper, but see their detailed description e.g. in [10]) showed, that sensitive detection of local wall thinning starts with application of certain non-zero magnetizing field amplitudes (but neither very large, substantially smaller than saturating amplitudes) and can be performed also with any larger ones. At the same time it was shown, that a larger amplitude does not mean *much* larger sensitivity in this measurement – the sensitivity only slowly approaches an asymptotic value. Any practical detection of a local wall thinning would then

1) choose a convenient value, A_C, of the amplitude,
2) do the measurement just with this amplitude,
3) find the corresponding most convenient value, F_C, on this loop and
4) finally draw the corresponding defect-detecting $1/\mu'(F_C, A_C, x)$-degradation function only.

Neither the time-consuming measurement of many loops and usually nor any careful demagnetization of the tested locality are necessary for practical detections of the local wall thinnings by MAT.

In [11] model experiments were performed: It was shown that MAT was an effective and promising tool for nondestructive detection of local thinning of a steel plate from the other side of the specimen. The method gave good results also in layered ferromagnetic plates. In the present work measurements were performed in a sample, where the area of wall thinning was covered by a real reinforcing shield. This case is close to the condition of real practical applications.

6. Conclusions

The above outlined result illustrated and confirmed that Magnetic Adaptive Testing is a suitable technique for detection/assessment of local material thinning in thick, layered, carbon ferromagnetic steel. The existence of an artificial slot was detected with a good signal/noise ratio and with a good reproducibility under a reinforcement shield that covered outside of the specimen. Even the 2.1 mm deep slot could be reliably detected through the 21 mm thick material and 8.5 mm thick reinforcement shield from the surface of the specimen, i.e. only the 7% depth of the slot as compared to the total thickness of the covers.

The described experiment proved principal applicability of the MAT method and practical instructions for its industrial application were listed in Section 5.

Acknowledgements

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References

[1] H.M. Crockett, J.S. Horowitz, J. Pressure Vessel Technology, 132 (2010) 024501-1.
[2] I. Nishiguchi, F. Inada, M. Takahashi, B. Ogawa, T. Inagaki, T. Ohira, K. Iwahara, K. Yamakami, E-Journal of Advanced Maintenance, 2 (2010/2011) 14-24.
[3] C.S. Angani, D.G. Park, G.D. Kim, C.G. Kim, Y.M. Cheong, J. Appl. Phys. 107 (2010) 09E720 - 09E720-3.
[4] J. Kim, G. Yang, L. Udpa, S. Udpa, NDT & E International, 43 (2010) 141-144.
[5] S. Xie, T. Yamamoto, T. Takagi, T. Uchimoto, in Electromagnetic Nondestructive Evaluation (XIV), Eds: T. Chady et al, IOS Press, 2011, pp. 203-210.
[6] H. Kikuchi, K. Sato, I. Shimizu, Y. Kamada, S. Kobayashi, IEEE Trans. Magn. 47 (2010) 3963-3966.
[7] H. Kikuchi, I. Shimuzu, K. Ara, Y. Kamada, S. Kobayashi, in Electromagnetic Nondestructive Evaluation (XIV), Eds: T. Chady et al, IOS Press, 2011, pp. 275-281.
[8] H. Kikuchi, Y. Kurisawa, K. Ara, et al., Int. J. Appl. Electromagnetics and Mechanics, 33 (2010) 1087-1094.
[9] I. Tomáš, J. Magn. Magn. Mat. 268/1-2 (2004) 178-185.
[10] I. Tomáš, G. Vértesy, „Magnetic Adaptive Testing", in Nondestructive Testing Methods and New Applications, M.Omar (Ed.), ISBN: 978-953-51-0108-6, (2012), InTech: http://www.intechopen.com/articles/show/title/magnetic-adaptive-testing.
[11] G. Vértesy, I. Tomáš T. Uchimoto, T. Takagi, NDT & E International, 47 (2012) 51-55.
[12] G. Vértesy, I. Tomáš T. Uchimoto, T. Takagi, E-Journal of Advanced Maintenance, 4 (2012) 96-104.
[13] I. Tomáš, O. Perevertov, JSAEM Studies in Applied Electromagnetics and Mechanics, T. Takagi and M. Ueasaka (Eds.), 9 (2001) 533-538.
[14] I. Tomáš, J.Kadlecová, G.Vértesy, IEEE Trans. Magn. 48 (2012) 1441-1444.