A CONCEPT OF NEW METHOD FOR NON-DESTRUCTIVE EVALUATION OF THE CORRELATION BETWEEN THE STRUCTURAL DEGRADATION AND MAGNETIC PROPERTIES OF SOFT MAGNETIC MATERIALS

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1. Motivation

The aim of work described in this paper is focused on the description of a novel approach to the non-destructive inspection of micro-structural changes induced by various factors, such as e.g. elevated temperatures, mechanical load, neutron irradiation, etc. These factors arise in industrial practice often in combination (heat and nuclear power plants, long-distance pipelines, etc.). Since long-term action of these effects may result in the decrease of the operation reliability or even fatal failure of such (in general very expensive) technological units due to irreversible structural changes associated with material fatigue, regular maintenance of key system components is of vital importance. Various, often very costly, destructive inspection methods based on e.g. Charpy V-notch test and microstructure evolution (dislocation/cluster density) are utilised, [1].

Therefore, a permanent ambition of the engineers and technicians along with the scientists is to find the compromise between maximal reliability and accuracy of those methods while keeping the operational costs as low as possible. This goal can be achieved by utilising preferably simple, non-destructive methods allowing fast, on-site automated data evaluation. For a long time, in case of various construction materials, such as e.g. low-carbon or standard steels characterised by relatively high electric conductivity, Eddy Current Testing (ECT) is well adopted. The first use of eddy current for non-destructive testing occurred already in 1879 when David E. Hughes used the principles to conduct metallurgical sorting tests, [2]. Since these materials exhibit in general soft magnetic properties, recently various methods based on the evaluation of either standard hysteretic properties - coercive field H_c, remanent flux density B_r, initial and amplitude permeability (μ_i, μ_a), etc. or using advanced, sophisticated methods (yet relatively simple) based either on the examination of Barkhausen noise parameters (Barkhausen Noise Analysis - BNA, [3]) or evaluating initial permeability and/or Preisach-like model parameters on a large set of minor hysteresis loops obtained at special experimental conditions (Magnetic Adaptive Testing - MAT, [4]. These advanced methods are of permanently growing importance, since they offer promising results. On contrary to e.g. ECT used to find macroscopic cracks and damages, they even allow to detect micro-structural changes.

2. Experimental details

Experimental equipment build-up from commercially available standalone measuring instruments controlled by tailor-made software was used, [5]. The samples are magnetised by means of high-power operational amplifier with an analogue feedback allowing control of driving current waveform, thus determining defined exciting magnetic field waveform shape $H(t)$. Since all the instruments used, including the power supplies, can be controlled via

USB/GPIB/LAN interface, remote management of experimental set-up can be utilised when needed. To avoid the influence of the demagnetising fields and other unwanted effects, magnetically closed ring-shaped samples have been used. The average values of the inner diameter $d = 45.7$ mm, outer diameter $D = 45.7$ mm and sample height $h = 4.79$ mm. These values were measured at various places by the calliper and screw micrometer with the accuracy of 0.01 mm. The samples were annealed in a standard commercially available furnace and the dimensions have also been verified after annealing.

3. Explanation of proposed method

The approach to be presented here is based on the idea described in [6], the sample is magnetised by the triangular waveform field. In a selected time instant t_{hold}, the field is held at a field value $H_{hold} = H(t = t_{hold})$ corresponding to this time instant for a sufficiently long time, i.e. larger than the time needed for all the transients in the material being damped out. t_{hold} is chosen for whole descending branch of the hysteresis loop ($H(t)$ decreasing from $+H_m$ to $-H_m$) with the step of $-0.05H_m$, thus H_{hold} covers the whole range of applied field $\langle -H_m; +H_m \rangle$. Holding the field at the ascending branch gives the same values, symmetrical with respect to BH coordinate system origin, so that the measurement is not necessary. Even if the exciting field is kept constant, due to the relaxation effects the magnetic flux density continues to settle towards a certain steady-state value B_{steady} that strongly depends on t_{hold}, (or H_{hold}), see Fig.1. Note that the peak-to-peak noise of the exciting field is about 0.5 $A.m^{-1}$.

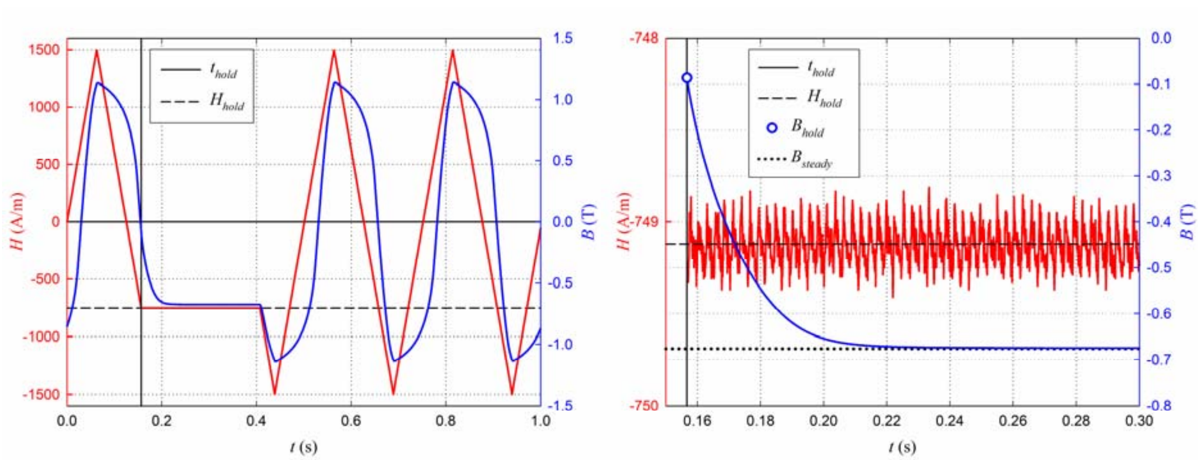
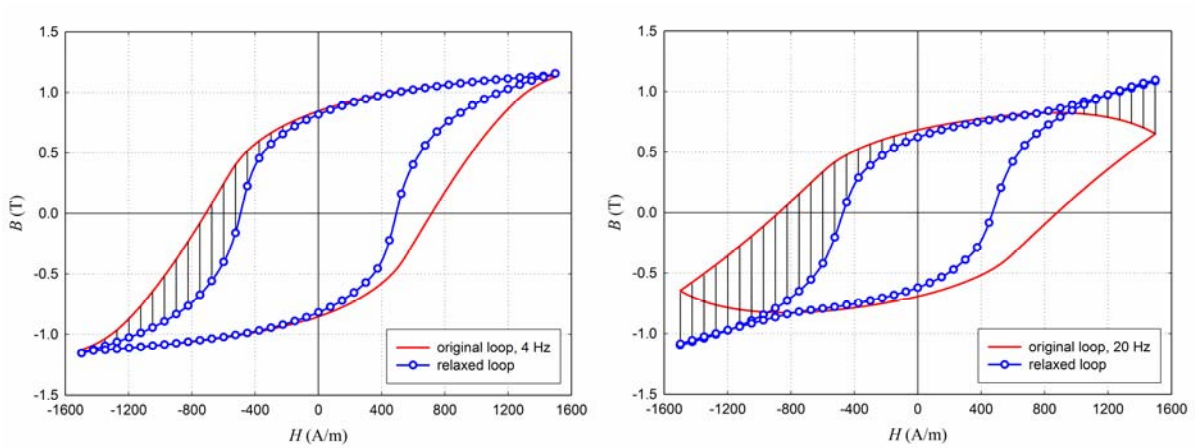


Fig.1: *An example of exciting field $H_m = 1500\ A.m^{-1}$ and corresponding flux density waveform with $H_{hold} = -0.5H_m$, (a) and the details of exciting field and flux density during "holding" the field, (b).*

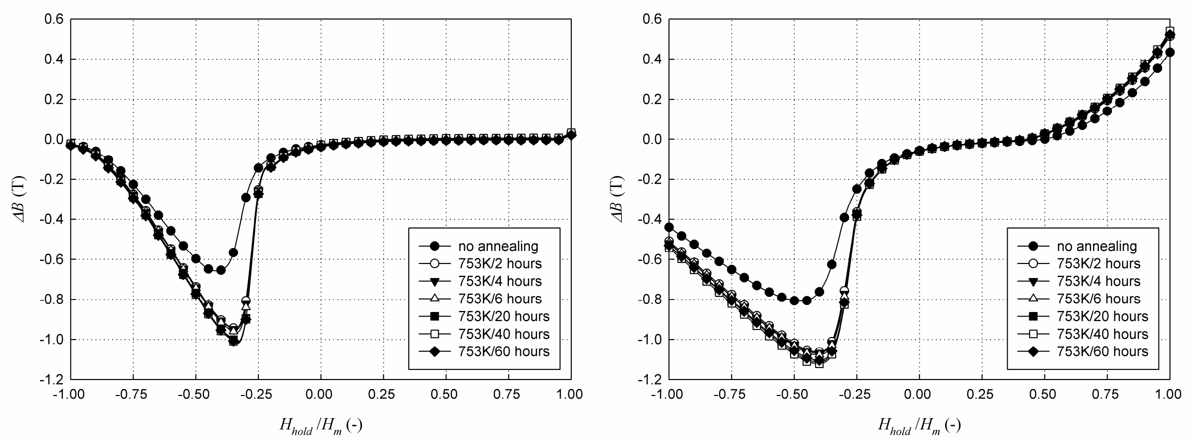
In Fig.2 is the original hysteresis loops of the as-cut sample (no artificial ageing) measured at the frequency $f = 4$ (a) and 20 Hz (b) along with "relaxed" steady-state loops obtained in such a way, that the original value of the flux density $B_{hold} = B(t = t_{hold})$ at H_{hold} was replaced by steady-state value B_{steady}. A significant dependence of the difference $\Delta B = B_{steady} - B_{hold}$, indicated by the vertical lines between descending (upper) branch of the original loop and the steady-state loop, upon H_{hold} is evident. As can be seen, the shape of steady-state loop depends on the frequency as well; it either differs from the quasi-static loop measured at extremely low frequencies, where the relaxation processes can be neglected, [6]. Note that the fundamental frequency has to be chosen as the compromise between the influence of eddy currents associated with the penetration depth of exciting field and sufficiently high level of the induced voltage.



a) *b)*

Fig.2: *Original along with "relaxed" hysteresis loops.*

The importance of frequency is well demonstrated in Fig.3, where the dependencies of ΔB upon H_{hold} normalised to H_m (H_{hold}/H_m ratio) at $f = 4$ and 20 Hz are displayed. The values of ΔB correspond to the lengths of vertical lines in Fig.2. At lower frequency, the relaxation is remarkable especially when $H_{hold}<0$ after the sample was magnetised to $+H_m$ and vice versa, meanwhile at higher frequencies the relaxation effects are visible also at the values of H_{hold} close to $+H_m$. A remarkable observation is, that for H_{hold} close to $+H_m$ the flux density during the relaxation increases, meanwhile below certain value of H_{hold} depending on various experimental conditions it decreases. This effects is either more visible at higher frequencies, see Figs.2b and 3b. Note that at $f = 20$ Hz and without annealing the highest absolute values of ΔB are about 0.8 T, which is comparable to the maximum achieved flux density values of the material (B_m = 0.825 T).

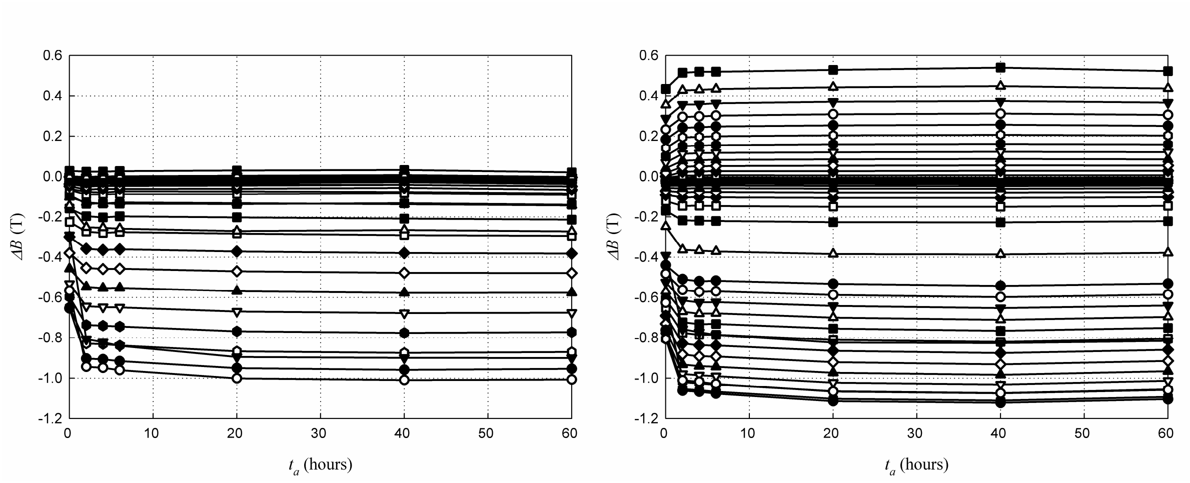


a) *b)*

Fig.3: *ΔB as a function of H_{hold}/H_m ratio at f = 4 Hz, (a) and f = 20 Hz, (b).*

4. Preliminary results and discussion

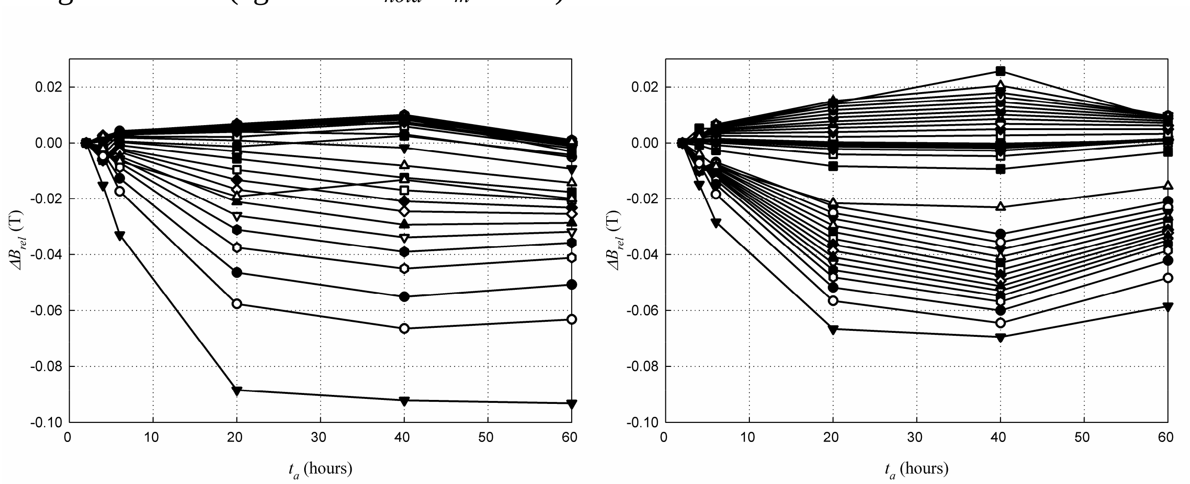
The influence of artificial ageing simulated by long-term heating at the temperature 753K for the ageing time t_a ranging from 0 to 60 hours can be seen in Fig.4, where the dependencies of ΔB upon t_a are given. From these dependencies the optimum values of H_{hold}/H_m ratio, at which the change of ΔB with t_a is the most pronounced and correlated with other data obtained independently by other testing method, can be selected.



a) *b)*

Fig.4: ΔB *as a function of* t_a *at* $f = 4$ *Hz, (a) and* $f = 20$ *Hz, (b).*
H_{hold}/H_m *ratio is the parameter of the curves.*

To see better the changes of investigated parameters (here ΔB) as a result of artificial ageing, a good practice is to evaluate the relative change of any chosen parameter with respect to some reference value corresponding to initial state of the material. An extraordinary care needs to be taken to the choice of such a reference point. Since the first measurements have been carried out on the sample that has been subjected to the mechanical processing including the hot rolling of steel sheet and cutting it into the ring form this is in general not a good choice because of residual stresses remaining in the material, having significant influence on the overall magnetic properties (often larger than the micro-structural defects themselves). This problem is clearly visible in Fig.4, where the differences between the values obtained for original as-cut samples ($t_a = 0$) and annealed for $t_a = 2$ hours are always the largest. This can be attributed to the fact, that internal stresses caused by cold-working are dominant in comparision with the structural properties of the sample material. Therefore, the measurements after initial annealing ($t_a = 2$ hours) aimed at stress removal, were used further as the reference ΔB_{ref}. In Fig.5 the values of ΔB related to the reference measurement $\Delta B_{rel} = \Delta B - \Delta B_{ref}$ are shown. The changes of ΔB_{rel} at $f = 4$ Hz are about -90 mT to about +10 mT depending on H_{hold}/H_m ratio, the highest change achieved for $H_{hold}/H_m = -0.3$ is -93.2 mT. At $f = 20$ Hz, ΔB_{rel} changed from about -70 mT to about +26 mT, the highest change was -69.4 (again for $H_{hold}/H_m = -0.3$).



a) *b)*

Fig.5: ΔB_{rel} *as a function of* t_a *at* $f = 4$ *Hz, (a) and* $f = 20$ *Hz, (b).*

5. Conclusions

A new experimental technique for non-invasive evaluation of the structural properties of construction materials affected by various kinds of applied load, based on the evaluation of properly selected soft magnetic properties, is proposed. The main advantage of the presented method is that since the measurement as well as data acquisition and processing can be fully automated (once the development of controlling software is finished), the inspection of device/material under testing becomes a routine task. Moreover, possible systematic errors during the measurements are well eliminated because of the fact that the changes of evaluated properties are normalised to the first reference measurement.

One can expect a lot of valuable information hidden in the experimental data. An imperative question arises - how to reveal this information. The future work to be done is thus associated with the key challenge - reliable interpretation of obtained data, especially its correlation with microscopic structural changes evoked by heat treatment, long-term mechanical load, neutron irradiation, etc.

Acknowledgement
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