ADAPTIVE TESTING OF MATERIALS USING PREISACH MODEL PARAMETERS VARIATIONS – INTRODUCTORY TESTS

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Summary A new diagnostic method (MAT – Magnetic Adaptive Testing) for non-destructive testing of ferromagnetic construction materials (i.e. iron based) under mechanical stress is under development, [1]. The method is based on the investigation of the correlation between the mechanical load and the parameters of Preisach-like model describing magnetic properties of such materials as the differential permeability matrix. To get the set of model parameters needed, a number of minor hysteresis loops under defined exciting magnetic field strength waveform shape $H(t)$, especially with constant field change rate $dH(t)/dt$ required (which implies the induced voltage to be proportional to the differential permeability), is to be measured. The influence of initial magnetic state of the investigated material, algorithm of demagnetisation process, the slope of time dependence of exciting magnetic field on the signal-to-noise ratio and stability of the measured signal is discussed.

1. INTRODUCTION

Iron-based materials belong to an important and high-volume class of construction materials, where non-destructive testing (NDT) of degenerative changes is a very important task from the point of view of a safe operation. Electromagnetic methods of NDT of metallic materials belong to the most used, mainly because of simplicity and thus the cost. The magnetisation processes in such construction materials go mainly through the domain wall motion, majority of which is an irreversible shift from one inhomogeneity to another. Consequently the wall motion is the main factor responsible for hysteretic ferromagnetic properties. Each magnetic inhomogeneity is associated with structural inhomogeneity (dislocations, inclusion, internal stresses, etc.). Hence the integral hysteretic parameters, such as the remanent flux density and coercivity, determined from the hysteresis loop are often used for fast qualitative indication of structural inhomogeneity, [2, 3]. Also the spectral analysis of time dependences of magnetic quantities determining the shape of hysteresis loop has often been used, [4]. These integral parameters are in general too insensitive to fine structural changes. For this reason attention has been put on "finer" analysis methods that can be divided into three basic approaches:

- detailed analysis of differential susceptibility during applied mechanical stress, where the high sensitivity to the distribution of dislocations is reported [5],
- new approaches to the measurements and analysis of Barkhausen noise [6],
- utilisation of Preisach model of magnetic hysteresis, that can be used for the definition of the scale of non-standard hysteresis parameters (Tomáš, Bertotti).

The main goal of the preliminary phase of this research is the preparation of automated measuring system allowing measurement of large amount of minor loops needed for the determination of Preisach-like model parameters. At this stage, the experimental equipment and software for instrument control, data evaluation including demagnetisation procedure optimisation has been designed and tested.

2. THEORETICAL CONSIDERATIONS

If any category of magnetic quantities has to be used for the material analysis, the set of minor hysteresis loops has to be measured. The loops are measured as a function of applied field h_A which is altered within a set of exciting field amplitudes h_B changing with step Δh_B. Thus the obtained magnetic parameters can be arranged in matrices whose elements are determined by two values – discrete field value h_{Ai} and minor loop amplitude h_{Bj}, [1].

One of quantities highly sensitive to mechanical stress applied to the sample is the differential permeability. The relative differential permeability is defined as

$$\mu_{\mathrm{diff}}(t)=\frac{1}{\mu_0}\frac{dB(t)}{dH(t)}=\frac{1}{\mu_0}\frac{\frac{dB(t)}{dt}}{\frac{dH(t)}{dt}} \quad , \tag{1}$$

where μ_0 is the vacuum permeability. If a constant field change rate $|dH(t)/dt| = \text{const.} = c$ is provided and all the conditions for homogeneous magnetisation are satisfied, then the differential permeability is directly proportional to the voltage induced in pick-up coil

$$\mu_{\mathrm{diff}}(t)=\frac{|v_{\mathrm{ind}}(t)|}{N_2\cdot S\cdot c\cdot\mu_0} \quad , \tag{2}$$

where N_2 is the number of sensing turns and S is the cross-sectional area of the sample. Thus, the differential permeability can be calculated directly from the measured induced voltage without necessity of using any kind of hardware or numerical integration procedure. Since the applied field is a linear function of time $H(t) \approx c{\cdot}t$, the time instant as a variable can be substituted by the applied field and thus the differential permeability can be understood as the function of the applied field,

$$\mu_{\mathrm{diff}}(t)=\mu_{\mathrm{diff}}(h_A) \quad . \tag{3}$$

The permeability belonging to the particular minor hysteresis loop can be characterised by the second variable - exciting field amplitude h_B. After proper discretisation of applied field, the permeability matrix corresponding to the set of minor hysteresis loops can be determined by the elements

$$\mu_{ij} = \mu_{diff}\left(h_{Ai}, h_{Bj}\right) \quad . \tag{4}$$

In case of constant field change rate the differential permeability matrix elements can be easily obtained from the measured induced voltages as functions of applied field.

Similarly, the discretised Preisach distribution function can be found as the derivative of differential permeability against h_B values

$$P_{ij} = \left.\frac{\partial \mu_{diff}\left(h_{Ai}, h_B\right)}{\partial h_B}\right|_{h_B = h_{Bj}} \quad . \tag{5}$$

An utilisation of rigorous identification process of Preisach function is not a necessity, because the primary task is not a model simulation of the magnetisation process.

The main idea of magnetic adaptive testing method is the comparison of the magnetic parameters matrices obtained before and after some mechanical loading. The comparison reveals which matrix elements are the most sensitive to structural changes due to mechanical stresses, i.e. can be used as "operating" values of h_A and h_B.

3. EXPERIMENTAL SET-UP

In the first phase we tested the parameters on magnetically closed samples only, where the influence of external stray fields and demagnetisation effect can be minimised. The block diagram of a conventional hysteresisgraph is in Fig. 1. The primary winding of the sample (N_1) is excited by known current waveform shape via power amplifier (AMP) acting as voltage-to-current converter with input voltage provided by an arbitrary waveform generator (ARB). The voltage across standard resistor (R_N) and the voltage induced in the secondary winding (N_2) and (optionally) amplified by a low-noise pre-amplifier (not shown) are simultaneously sampled by two equivalent digital voltmeters (DVM1) and (DVM2). All the instruments are controlled via GPIB bus. The advantage of this approach is a significantly larger true resolution and natural noise reduction thanks to the multi-slope integration method in principle acting as low-pass filter compared to the usage of digital oscilloscope or A/D conversion plug-in cards. On the other hand, the sampling rate of the voltmeters is limited, so that the measured signals should have relatively low frequencies (less, than few Hz), as discussed in [7, 8]. Thus, only quasi-static magnetic parameters can be measured.

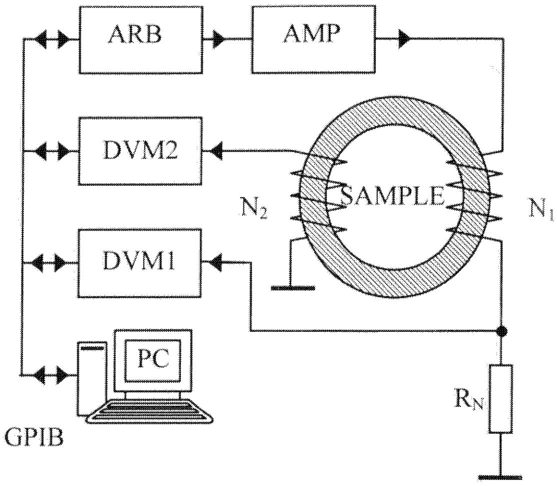

Fig. 1. The block diagram of experimental equipment.

The magnetic flux density is obtained from the induced voltage using numerical integration. Any DC-offset of pre-amplifier and other components involved in the signal path was always removed by software **before** the integration to avoid unwanted linear term (drift) of the integrated signal caused by the offset integration. All necessary data filtering, smoothing and calculations (differential permeability, remanent flux density, coercivity, etc.), were performed by means of developed control software.

Note that at higher frequencies the multiple signal periods averaging feature of modern digital oscilloscopes can be used efficiently for noise removing and increase the effective resolution. Furthermore, low sampling rate is not a problem, since the relative changes of permeability peaks are indirectly proportional to the field change rate and thus the differential permeability becomes less sensitive to mechanical stress at higher frequencies, [9].

4. DEMAGNETISATION PROCEDURE

An inseparable part of the measurement is the sample demagnetisation, since in the case of wrong demagnetisation the minor hysteresis loops become non-symmetrical, especially in weak exciting fields. The influence of starting demagnetising field amplitude and change rate (associated with dynamic effects) and other factors was investigated long ago, see e.g. [10, 11]. It was found out that the starting amplitude should be large enough to prevail over previous remanent state of the sample, the decrease of field amplitude should be smooth (so that large number of demagnetisation cycles needed) and the field change rate should be as low as possible. All these factors result in very long times needed for the sufficient demagnetisation. Moreover, the shape of virgin and/or amplitude curve is important, [12].

To avoid too long demagnetisation times, an algorithm for the determination of a proper demagnetisation waveform has been verified, which is based on the utilisation of the measured amplitude and/or virgin curve of the sample. The decrease of demagnetising signal amplitude is derived from either curve in such a way that each successive demagnetisation cycle amplitude drops down with equidistant step of magnetic flux density lying on amplitude curve. The necessary amplitude values were obtained by cubic spline interpolation of the amplitude curve. Thus, minimum number of demagnetisation cycles is required. An example of demagnetisation waveform to be downloaded to arbitrary waveform generator is shown in Fig. 2.

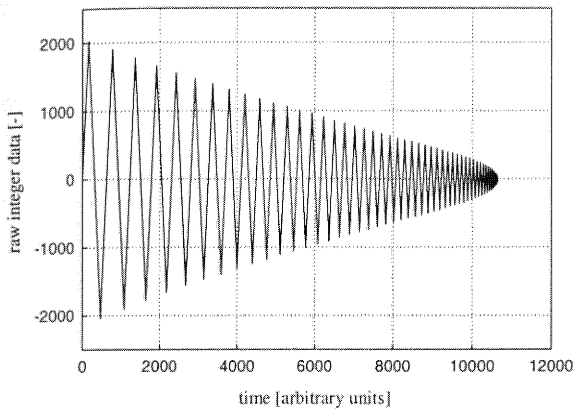

Fig. 2. Raw data representing demagnetisation waveform – exciting field strength. The envelope of triangular wave is derived from the requirement of equidistant flux density decrease.

The reason why the equidistant step of the flux density is given by the slope of amplitude curve at low fields, where small change of exciting field causes a big jump of the flux density. Thus the sample may possibly not to be demagnetised properly. The amplitude of waveform depends on remanent state and the frequency of wave is determined by required field change rate for demagnetisation.

5. Results and discussion

The quality of demagnetisation procedure was verified by a number of manners. Firstly, the sample was pre-magnetised by sufficient number (at least 3) of periodic cycles with the amplitude far below the saturation. Then one minor hysteresis loop was measured at the same amplitude and checked for positive and negative remanent flux density and coercivity. Nevertheless, the crucial criterion of a good demagnetisation was the symmetry of minor hysteresis loop – the positive and negative halves of the loop should be equal. If the positive and negative values were not identical within prescribed value (e.g. 0.1%), the demagnetisation was repeated again.

The measured dependencies of induced voltage with respect to exciting magnetic field strength are shown in Fig. 3. The difference between similar dependencies found in [1] is the way of measurement. In the experiment described in [1] the induced voltage was measured continuously from the demagnetised state with increasing amplitude of triangular exciting field, meanwhile in our case we measured the set of minor hysteresis loops each preceded by a sufficient number of pre-magnetisation cycles as described above.

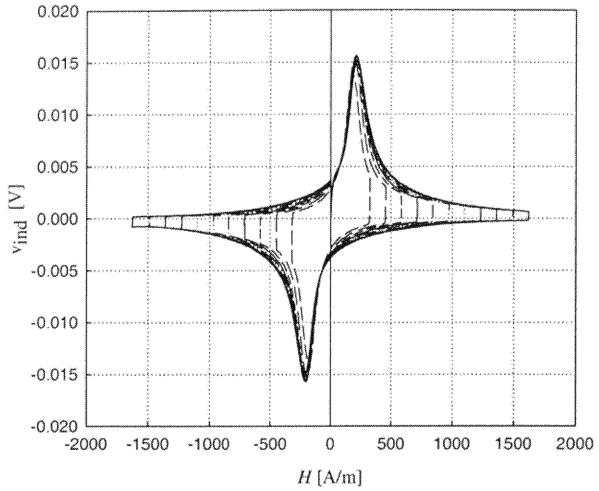

Fig. 3. The induced voltage versus the exciting magnetic field strength.

The comparison of differential permeability calculated as numerical derivative from the measured hysteresis loop (Eq. 1, solid line) and given by Eq. 2 (open circles, only every 3rd measured point is shown for clarity) can be seen in Fig. 4. One can see perfect agreement between both curves except for the peaks at maximum and minimum values of exciting field (horizontal axis) - the artefacts caused by numerical differentiation, which is in principle sensitive to signal noise and inhomogeneities. Note that no additional numerical filtering, smoothing and/or averaging of data that may result in information loss were used; otherwise the differences between both methods were observable.

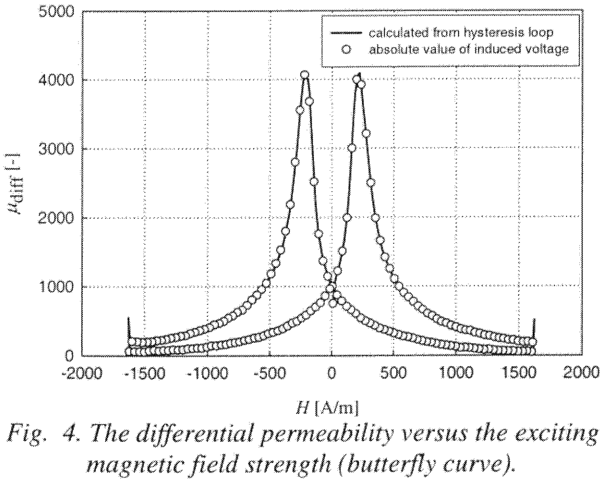

Fig. 4. The differential permeability versus the exciting magnetic field strength (butterfly curve).

To save time needed for the measurements, yet another trick was used. Instead of measuring the set of minor loops from demagnetised state up to saturation with successively increased exciting field amplitude, the amplitudes were changed in reverse order – from maximum to minimum. This approach allows obtaining of almost perfectly symmetrical induced voltage curves and corresponding hysteresis loops from which the differential permeability can be calculated.

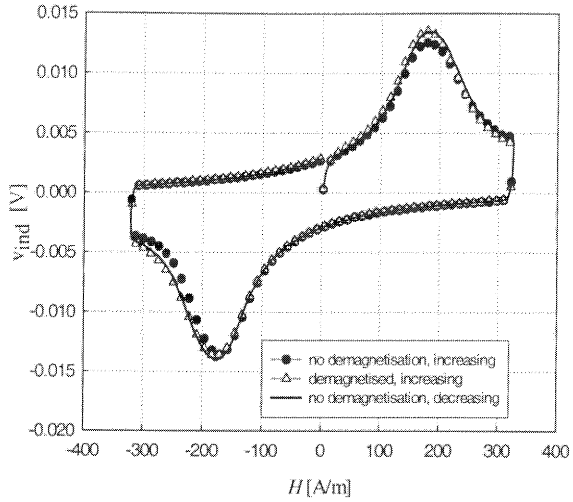

Fig. 5. The comparison of induced voltage versus the exciting magnetic field strength at weak fields measured by different methods.

As can be seen in Fig. 5, in case of decreasing the field amplitude the demagnetisation was not necessary anymore (solid line), meanwhile in case of previous technique, when the sample was not demagnetised (solid circles), the hysteresis loops and permeability curves measured at weak fields were not symmetrical. A very good agreement between the curves obtained by standard way with demagnetisation (open triangles) and by "tricky" way without demagnetisation (solid line), can be observed. If the standard method without demagnetisation was used, significant differences and non-symmetry appear (solid circles).

6. CONCLUSIONS

The comparison of differential permeability acquired from the measured data by different methods at constant exciting field change rate has shown very good agreement – obviously it makes no sense to use numerical differentiation of hysteresis loops in this situation, since the flux density is obtained by the integration of induced voltage. On the other hand, the numerical differentiation can be utilised as the convenient method for the calculation of differential permeability in the cases where the field change rate is not constant and therefore Eq. (2) cannot be used (i.e. sinusoidal excitation, etc.). Another issue is the optimum field change rate *c*. If the field changes too rapidly, the dynamic effects and eddy currents influence the shape of induced voltage dependencies in such a way that the peaks are not so sharp and the relative changes of permeability matrix elements are less evident. Alternatively, if the field change rate is too low, the induced voltage levels drop down resulting in noisy signal. Moreover, Barkhausen noise becomes significant in this case.

If the set of hysteresis loops is measured from saturated state down to minimum amplitude required, the sample demagnetisation could be omitted. Thus the time needed for the experiments is significantly reduced. On the other hand, the verified demagnetisation algorithm can be used for comparative measurements of anhysteretic curves that can be used for non-destructive testing of magnetic materials, too. In that case perfect demagnetisation is unavoidable.

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