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A NEW APPROACH TO THE EVALUATION OF MAGNETIC PARAMETERS FOR NON-DESTRUCTIVE INSPECTION OF STEEL DEGRADATION

Elemír Ušák*

Various conventional magnetic parameters, such as the coercivity, remanence, hysteresis loop area, initial permeability, *etc* as well as non-standard parameters evaluated by means of Magnetic Adaptive Testing (*eg* relative differential permeability) are strongly affected by the microstructure of tested materials. Thus, the relationship between these parameters and microstructural changes due to thermal and/or mechanical treatment or even long-term neutron irradiation can be used as a good tool for non-destructive inspection of these changes, possibly associated with material fatigue. In this work, a new approach to the evaluation of magnetic parameters as well as some preliminary results obtained on the samples exposed to artificial ageing are to be presented.

Keywords: non-destructive evaluation, microstructural changes, artificial ageing, Magnetic Adaptive Testing (MAT)

1 INTRODUCTION

Nowadays, non-destructive investigation of various construction materials gets more and more important, especially in the fields where the security of operation is at the first stage, such as the pressure vessels in nuclear power plants, pipelines, boilers, *etc*. A significant, permanently developing class of non-destructive evaluation methods, *eg* Eddy Current Testing (ECT), Barkhausen noise testing (BN), Magnetic Adaptive Testing (MAT), Magnetic Flux Leakage testing (MFL), *etc* is based on electromagnetic principles. The main advantage of all these techniques is that the experimental data acquired contain much more information than that obtained by means of conventional experimental methods. Usually the only problem is an unambiguous interpretation of experimental results.

This paper is concentrated primarily on the performance of the investigation of conventional magnetisation curve parameters in comparison with one of the above mentioned techniques - MAT method. The conventional magnetic parameters are often related either to sample saturation (*eg* coercivity, remanence) or extremely low fields (initial permeability). In both cases there can arise significant difficulties in obtaining experimental data, especially when the samples to be measured are *open*. In such a case, owing to demagnetisation fields, the saturation could require substantially larger exciting currents comparing to magnetically closed (*eg* ring) samples. Furthermore, the determination of the exciting field in the sample volume becomes awkward, since it requires advanced calibration techniques. At the same time, the measurements of low fields are in general difficult to carry out as well, especially at low frequency regions required in quasi-static mode. For these reasons, a new approach based on relatively simple experimental procedures along with somewhat non-traditional evaluation methodology that allows using of a simple and relatively inexpensive experimental set-up will be demonstrated here.

2 SAMPLES USED AND EXPERIMENTS

The samples made of Fe-1 wt.% Cu alloys compliant with the standards for Charpy v-notch test undergone to thermal ageing and cold-rolling have been tested. The overall treatment of samples is summarised in Table 1.

Table 1. Sample treatment summary

Sample	cold-rolled before ageing (%)	ageing time at 753 K (min)	cold-rolled after ageing (%)
BD1	0	0	0
BD2	10	0	0
BC1	10	20	0
BC2	10	20	5
BC3	10	20	10
BC4	10	20	20
BC5	10	200	0
BC6	10	200	5
BC7	10	200	10
BC8	10	1800	0
BC9	10	1800	5
BC10	10	1800	10

The influence of such an artificial ageing was evaluated by means of the analysis of conventional magnetic parameters, as well as the differential permeability μ_{diff} examined by means of MAT, [1]. All these parameters were found from the sets of quasi-static minor hysteresis loops measured at exciting magnetic field with *triangular waveform* (required for MAT) and specified field change rate. The families of loops at *defined constant field change rate* were measured by means of a conventional PC-controlled hardware using double-yoke magnetising system described in [2]. The field change rate value of 500 $A.m^{-1}s^{-1}$ was chosen as a compromise between sufficiently low frequencies and sufficiently high signal levels of induced voltage. The obtained data have been used for the evaluation of standard magnetisation curve parameters as well.

* Department of Electromagnetic Theory, Slovak University of Technology, Faculty of Electrical Engineering and Information Technology, Ilkovičova 3, 812 19 Bratislava, Slovakia; elemir.usak@stuba.sk

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3 COMMENTS TO DATA ACQUISITION AND PROCESSING

First, the sets of measured minor hysteresis loops have been analysed by means of MAT. Only the values of relative differential permeability $\mu_{diff}(h_A, h_B)$ from the operating space regions (two-dimensional matrix where the first parameter is determined by the discretised values of applied field h_A (A/m) meanwhile the second one represents the maximum applied field at which a particular minor loop has been measured – h_B (A/m), [1]) satisfying *all the chosen criteria*, such as the sensitivity, stability, linearity and monotonicity are given here. In more details, the selected values of μ_{diff} should be defined at the points of operating space given by Cartesian coordinates (h_A, h_B) where the sensitivity (high relative change) to material ageing is the highest. High stability simply means low surface-curvature of the function of two variables $\mu_{diff}(h_A, h_B)$ – a small deviation from the measurement parameters h_A and h_B from optimal values found by MAT analysis should not lead to significant changes in the permeability). Linearity is required to provide similar sensitivity in a whole range of material degeneration/ageing and monotonicity is necessary for being able to find an inverse function. There were the regions of operating space where μ_{diff} was even significantly more sensitive to structural changes and thermal treatment, but it did not meet the requirements on at least one of the above mentioned criteria on the dependencies.

Afterwards, the same loops were used to acquire the conventional magnetisation curve parameters by the approach described later. The coercivity was found by the extrapolation of the dependencies of minor-loop coercivity as a function of maximum exciting field value H_m to an infinite field. An example of such dependence is shown in Fig. 1a. The dependence is fitted by three-parameter sigmoidal (logistic) fitting function given as

$$H_c = \frac{a}{1+\left(\frac{H_m}{c}\right)^b} \qquad (1)$$

where the parameter a corresponds to the value of saturated coercivity for infinite exciting field $H_{c\infty}$, the parameters b and c are out of interest. Note that several types of similarly-shaped fitting functions (*eg* $H_c \approx arctan(H_m)$, *etc*) were tested as well, giving almost the same results. The differences were within a few tenths of a percent. In commercially available graphing tools one can find a variety of other suitable fitting functions (needless to mention, with no physical meaning here).

The same procedure was used for the estimation of the saturation remanent flux density, the parameter a in this case coincides with the value of the infinite-field remanence $B_{r\infty}$, see Fig. 1b. Another advantage of this approach is that, since the slope is kept the same, increasing maximum field is associated with decreasing the frequency. As a result, $H_{c\infty}$ and $B_{r\infty}$ correspond to $f = 0$, thus representing the parameters of *truly static saturated hysteresis loop*.

This methodology could bring the benefits especially in the cases when the ratio H_m/H_c is large (say, >100) normally resulting in the decrease of low-field accuracy (since the error of measuring weak fields, associated with the resolution of AD conversion, is large for particular measuring range of the data acquisition hardware needing to cover all the exciting field swing from $-H_m$ to $+H_m$). Autoranging should be avoided since it brings an uncertainty into the data acquisition timing as well as the overall accuracy – the exact time instant of taking the samples is affected by unpredictable time delays after changing the range and the accuracy could be decreased due to non-zero settling times (associated with transients) of measuring amplifiers and other auxiliary circuitry after changing the gain. Moreover, there could be no need to measure the magnetisation curves at too high exciting fields often needed to saturate the sample sufficiently resulting in adequately demanding hardware. Too high exciting fields are undesirable in MAT analysis as well, since it works best in the maximum fields below the sample saturation (H_m/H_c less than about 3-5, depending on the hysteresis loop shape).

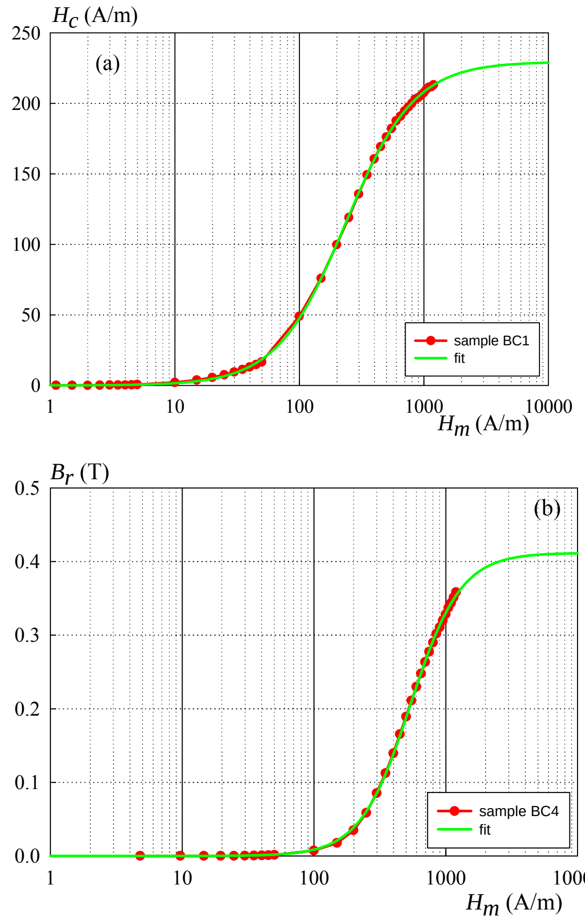

Fig. 1. Coercivity H_c (a) and remanence B_r (b) as a function of maximum field value H_m.

The amplitude curves obtained from the minor loops measured at low H_m (0.5 to 50 A/m) were used to estimate the relative amplitude permeability extrapolated to zero field μ_{a0} (*ie* initial permeability). The relative amplitude permeability (calculated from B_m and H_m) as a function of H_m was fitted by the second-order polynomial

$$\mu_a = a(H_m)^2 + bH_m + c \qquad (2)$$

The fitting coefficient c corresponds to the zero-field permeability μ_{a0}. In some cases the values of fitting coefficient a were small enough to neglect the quadratic term (*ie* the exciting field was within the Rayleigh law region). The advantage of presented approach is that there is no need for complicated low-field measurements affected by the noise, offsets and drifts of measuring equipment, especially in quasi-static (or DC) mode.

The hysteresis loops area A_{loop} at H_m = 1200 A/m was evaluated as well. The area is calculated by means of well-known algorithm calculating the area of the polygon given by the set of measured data points with two rectangular coordinates in the plane (implemented *eg* in a simple MATLAB function *polyarea(X, Y)*), [3]; the second method uses the discrete Fourier transform (DFT) for the computation of amplitude and phase spectra of the magnetising field strength and magnetic flux density waveforms respectively. From the spectra the loop area can be calculated easily. Both methods in general give the same results within discretisation errors of the sampled waveforms.

4 RESULTS AND DISCUSSION

The influence of thermal ageing on various magnetic parameters is shown in Fig. 2; influence of cold-rolling is summarised in Fig. 3. In these figures, all the data are normalised to the values measured on the initial sample (the first one in the given sample sequence). The most convenient parameter(s) has(ve) to be chosen as a compromise between the sensitivity on the one side and the linearity and monotonicity on the other side. From the figures one can see that some parameters are almost insensitive to either the cold-rolling or thermal ageing, meanwhile in some cases there are large relative changes (as an extreme case one can point out the zero-field permeability μ_{a0} changing from 1 to about 6.5 as a result of thermal ageing up to 1800 min., see Fig. 2). Since the zero-field permeability exhibits in most cases the worst linearity and monotonicity, it can not be assumed as a good measure of artificial ageing. In any case, to make sure the reliability of such non-destructive inspection methods, the dependencies obtained have to be reproducible for a large set of samples made of a given material. The remanence $B_{r\infty}$ and loop area A_{loop} show the behaviour similar to each other, the sensitivity to ageing is less than for μ_{a0}.

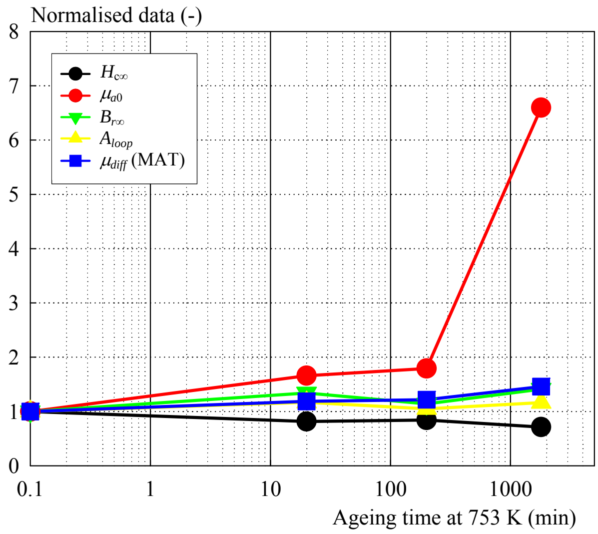

Fig. 2. The influence of thermal ageing on various magnetic parameters. Sample sequence: BD2–BC1–BC5–BC8

Again, the linearity and monotonicity is not as good as it would be desirable. Finally, two competitors remain – the coercivity and $H_{c\infty}$ and differential permeability μ_{diff} – one representing conventional parameters usually shows the best linearity, meanwhile the second one displays better sensitivity. Moreover, the choice of operating region of μ_{diff} can further be optimised by means of MAT procedure.

5 CONCLUSIONS

The coercivity as well as the differential permeability at certain operating point on selected minor loops seem to be the most convenient parameters for the characterisation of microstructural changes (always monotonous, sometimes even linear). In most cases, coercivity exhibits the best linearity. The remanence and hysteresis loop area have similar behaviour (similar trends to rise/fall), the sensitivity to artificial ageing is the lowest. The zero-field permeability shows in some cases the highest sensitivity to mechanical and/or thermal treatment, but it is not a reliable parameter (non-linear, not always monotonic).

The presented approach of data evaluation along with the simple experimental equipment can be used even for on-site non-destructive testing of large objects made of ferromagnetic construction materials in the industry and outdoor environment.

Further work focused on the detailed investigation of the correlation between the results presented in this work and the fundamental experimental data associated with the microstructural changes and the mechanical properties (such as *eg* the dislocation density, Vickers hardness, ductile-brittle transition temperature (DBTT), *etc*) of the samples under investigation will be carried out in the near future.

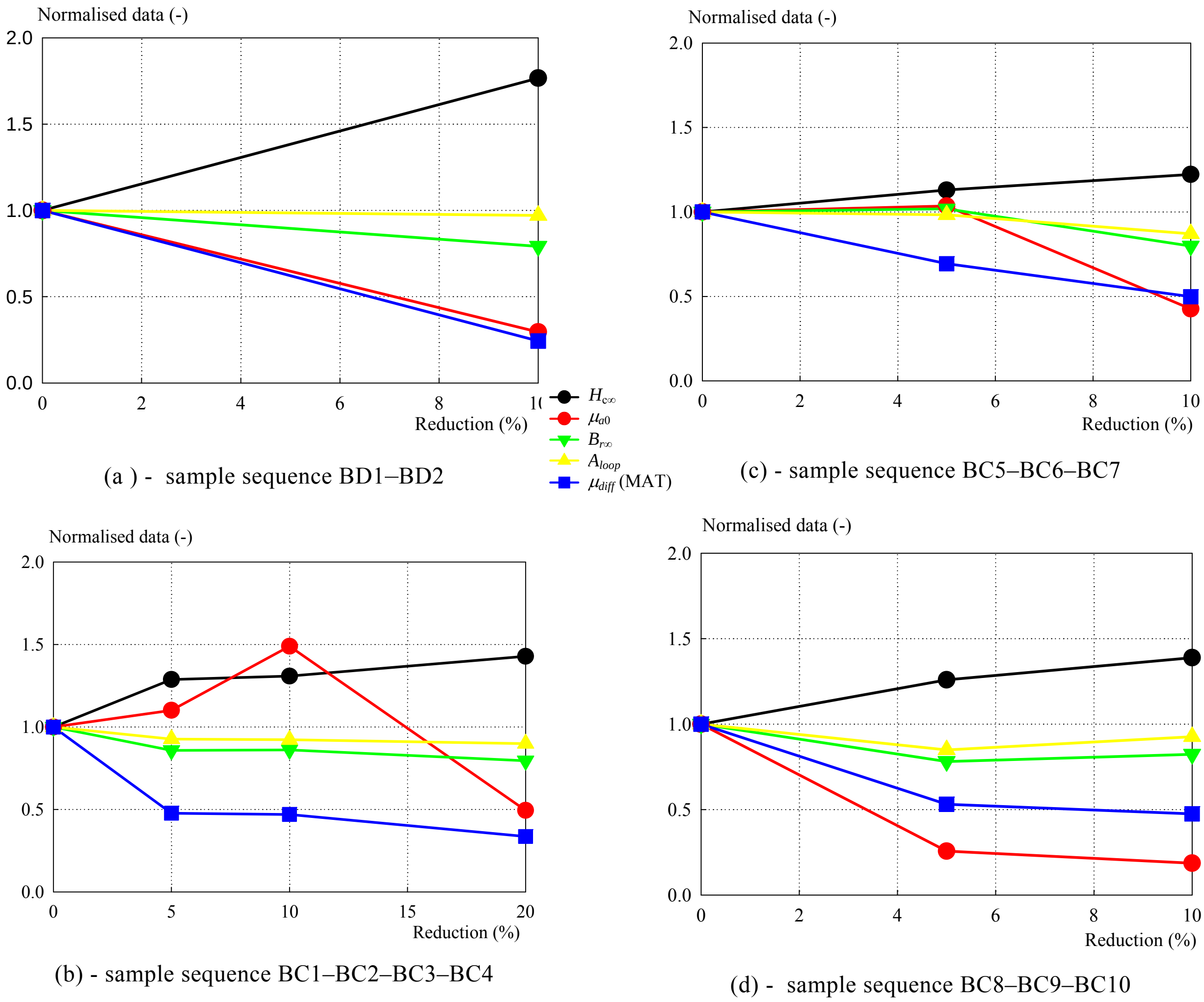

Fig. 3. The influence of cold-rolling on various magnetic parameters.

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References

[1] Tomáš, I.: Non-destructive magnetic adaptive testing of ferromagnetic materials. Journal of Magnetism and Magnetic Materials 268, (2004), 178-185

[2] Ušák, E. – Bydžovský, J. – Stoyka, V. – Kováč, F.: Analysis of Capabilities of Small Double-Yoke Single Sheet Tester. Journal of Electrical Engineering **59**, No. 7/s, (2008), 21-24

[3] Beyer, W. H. (Ed.). CRC Standard Mathematical Tables, 28th ed. Boca Raton, FL: CRC Press, (1987) 123-124

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Elemír Ušák (Assoc Prof, PhD), born in Nižná pri Piešťanoch, Slovakia, 1965. Graduated from the Faculty of Electrical Engineering, Slovak University of Technology, Bratislava in Solid State Physics branch, 1988 and received the CSc (PhD) degree in Theory of Electromagnetism in 1996. After habilitation in 2000 he became an associate professor at the Department of Electromagnetic Theory of FEIIT SUT in Bratislava.