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Influence of rate of change of magnetization processes on sensitivity of magnetic adaptive testing

Ivan Tomáš [a,*], Gábor Vértesy [b], Jana Kadlecová [a]

[a] Institute of Physics, ASCS, Prague, Czech Republic
[b] Research Institute for Technical Physics and Materials Science, Budapest, Hungary

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ABSTRACT

The rate of change of magnetizing field (field-slope), applied for the nondestructive method of magnetic adaptive testing, influences both signal-to-noise ratio and sensitivity of the chosen magnetic parameters with respect to the investigated degradation of the ferromagnetic material (degradation functions). Dependence of the degradation functions sensitivity on the field-slope is analyzed in this paper. It is shown that whereas sensitivity of the top-responsive degradation functions from around the top permeability of the nondegraded (reference) material drops down with increasing field-slope, sensitivity of the mild-responsive degradation functions from regions with lower permeability of the reference material is frequently field-slope-independent. The most favorable choice of the best degradation functions and of the proper magnetizing field-slope remains to be a question of optimum adaptation of the tests both to the investigated material and to the applied measuring technique.

1. Introduction

Magnetic measurements are frequently used for characterization of nonmagnetic changes in structure of industrial ferromagnetic materials, because the level of ease or difficulty of processes of their magnetization is closely related to the state of microstructure of the materials. This fact makes magnetic measurements an evident candidate for nondestructive testing, for detection and characterization of structural modifications and/or defects in materials and in manufactured products made of such materials [1–3].

Structural nonmagnetic properties of ferromagnetic materials have been nondestructively tested by the traditional magnetic hysteresis methods for a long time with fair success. A number of techniques were suggested, developed and currently used in industry, see e.g. Refs. [4,5]. They are mostly based on detection of the material structural variations via variation of the traditional parameters of their *major* hysteresis loop, such as coercive field, remanent magnetic induction, maximum permeability, and a few others. At first, these magnetic parameters are experimentally correlated with independently measured real structural/mechanical characteristics of the samples, and then from measurement of the former ones the latter can be determined. The point is that the magnetic parameters are measured *nondestructively and with less difficulty* than the real structural/mechanical characteristics, which in most cases can be learned destructively only. The few traditionally employed magnetic parameters are actually special points or slopes on the magnetic major hysteresis loop. They are, however, by no means the only available magnetic indicators of various nonmagnetic modifications of ferromagnetic materials. Correlation between alternative magnetic parameters and specific structural changes of the studied material, can possibly be even *better adapted* to each specific task.

A successful attempt how to introduce alternative magnetic parameters, *optimally adapted* to specific investigated nonmagnetic structural variations of specific materials has recently been considered in Ref. [6]. The method is called magnetic adaptive testing (MAT), it is based on measurement of families of magnetic *minor* loops, and by simple analysis of the correlations (referred to as the *degradation* functions) between the measured magnetic data and the independently measured real structural/mechanical characteristics of the step-by-step degraded samples, it determines the optimum degradation function/s for the task.

The method proved to be very suitable for sensitive nondestructive characterization of structural changes in ferromagnetic materials, see e.g. Refs. [7,8], and it was demonstrated in separate studies that neither the samples shape [9] nor various ways of magnetization of the samples [10] have detrimental influence on its applicability. Similarly as any other magnetic hysteresis methods (and actually as most of the nondestructive

* Corresponding author. Tel.: +420 721 873 360; fax: +420 286 890 527.
E-mail address: tomas@fzu.cz (I. Tomáš).

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methods as well), MAT is a *relative method*, i.e. it indicates relative modifications of the structural/mechanical characteristics of the samples with respect to properties of an earlier defined reference. As the typical application of these methods is determination of the degree of *degradation* of the material due to some (usually industrial) external influence, a nondegraded, virgin piece of the same material is regularly used as the reference. Then both the reference and the tested samples are magnetized under identical experimental conditions and relevant parts of the signals induced in the pick-up coils are compared. In order to maintain the magnetizing conditions steady, it is recommended to keep the rate of change of the magnetizing field *constant* (but for the sign, if minor loops are to be measured) through the whole measurement. Besides, it is necessary to set the rate of change of the magnetizing field (field-slope) *high enough* to get a sufficient signal-to-noise ratio, but it is advisable to set it at the same time *low enough* in order to minimize eddy currents and other dynamic effects and to make the measured data as straightforward as possible. The present paper investigates *influence of the value of the applied magnetizing field-slope on the MAT measurements*, on sensitivity of the optimum degradation functions in particular.

The most important features of the MAT method are reminded in Section 2. In Section 3 MAT is applied on a series of ring-shaped samples made of low-carbon steel, which was degraded by plastic deformation due to uniaxial mechanical tension. Several magnetizing field-slopes are applied and results of the MAT measurements are presented. The results are explained and discussed in Section 4, and suggestions are formulated. Section 5 summarizes the conclusions for optimum MAT application.

2. Method of magnetic adaptive testing

A detailed description of the method can be found elsewhere, e.g. in Ref. [6], here we emphasize only a few points important for the task of the paper:

MAT aims at finding optimum *degradation function/s* for the reference series of degraded samples, which are characterized by increasing values of a degradation coefficient, ε_k, ($k = 0,1,2,3,\ldots$). The degradation coefficient of the reference sample is ε_0. The induced voltage data are recorded in the shape of one family ($j = 1,2,3,\ldots$) of minor hysteresis loops for each ε_k-sample. The samples are magnetized by field, F, within the step-by-step increasing amplitudes, $-A_j \leqslant F \leqslant +A_j$. If the measurement is performed on magnetically closed thin-ring-shaped samples, with cross-section, S, each equipped with a pick-up coil with n turns, then the recorded signal, $U(t)$, for each jth loop and for each kth sample is proportional to the differential permeability, μ, as

$$U_{jk}(t) = -n{*}\mathrm{d}\Phi/\mathrm{d}t = -n{*}S{*}\mu(\mathrm{d}F/\mathrm{d}t, F, A_j, \varepsilon_k){*}\mathrm{d}F/\mathrm{d}t, \quad (1)$$

where Φ is magnetic flux in the ring and t is time.

Instead of keeping the signal and the magnetizing field in shapes of continuous time-dependent functions, it is practical to interpolate the family of data for each ε_k-sample into a discrete square (i, j)-matrix $U_{ijk}(F_i, A_j, \varepsilon_k)$, with a suitably chosen step, $\Delta A = \Delta F$. The degradation functions, f_{ij}, normalized by the reference sample, are then created from mutually corresponding matrix elements as functions of ε

$$f_{ij}(\varepsilon) = U_{ijk}/U_{ij0} = \mu(\mathrm{d}F/\mathrm{d}t, F_i, A_j, \varepsilon_k)/\mu(\mathrm{d}F/\mathrm{d}t, F_i, A_j, \varepsilon_0). \quad (2)$$

The first information on sensitivity and reliability of each degradation function is then obtained from a *sensitivity map*, i.e. from a 3D plot expressing by black-and-white shades the values of relative steepness of each degradation function within the (F_i, A_j) field-coordinates. Based on the preliminary information of the sensitivity map, the optimum *degradation function/s* are identified.

3. Experimental

The samples employed for this investigation were a series of circular rings with the nominal dimensions of the outer diameter 44 mm, the inner diameter 34 mm and the square cross-section $S = 5 \times 5\,\mathrm{mm}^2$. (Individual dimensions of each sample, which fluctuated by a few percent around the nominal ones, were taken into account in evaluation of the magnetic data.) Each of the samples was equipped with a magnetizing coil of 200 turns and a pick-up coil of $n = 100$ turns. The material of all the samples was low-carbon steel (CSN 12021), which was—shaped as flat plates 6 mm thick—plastically deformed by uniaxial tension to strains indicated in Table 1. The rings were carefully machined from the plates after the deformation.

A specially designed permeameter [11] was applied for measurement of families of minor loops of differential permeability of the magnetic circuit. The varying magnetization of each sample was achieved by application of a time-dependent magnetic field, $F(t)$, due to triangular waveform current, $I_F(t)$, in the magnetizing coil, with step-wise increasing field-amplitudes, A_j, corresponding to the step-wise increasing current-amplitudes, I_{Aj}. The rate of change in all the triangles was constant (but for its sign), namely $\mathrm{d}I_F/\mathrm{d}t = \mathrm{const.}$ for the current-slope and/or $\mathrm{d}F/\mathrm{d}t = \mathrm{const.}$ for the magnetizing field-slope, in each measured family of the minor loops and in any measurements mutually compared. The applied current-slopes and the corresponding field-slopes were $\mathrm{d}I_F/\mathrm{d}t = 0.5$, 4, 32 A/s, and $\mathrm{d}F/\mathrm{d}t = 0.8$, 6.4, 51.2 kA/m/s, respectively.

The sensitivity map of the degradation functions computed for the measurement with the field-slope $\mathrm{d}F/\mathrm{d}t = 0.8$ kA/m/s is plotted in Fig. 1 for the field-coordinates $-A_j \leqslant F_i \leqslant +A_j$, $0 < A_j \leqslant 3.6$ kA/m, with the step $\Delta A = \Delta F = 0.2$ kA/m. The f_{ij}-sensitivity maps for $\mathrm{d}F/\mathrm{d}t = 6.4$ and 51.2 kA/m/s are qualitatively similar to that in Fig. 1. Three interesting regions of the field-coordinates (F_i, A_j) can be seen in each of the sensitivity maps, with slight shifts of the extreme regions due to different field-slopes. The whitest regions indicate the most sensitive *increasing* degradation functions, the blackest region indicates the most sensitive *decreasing* ones. The typical, the most sensitive representatives of degradation functions, taken from each of the above mentioned regions are plotted in Fig. 2a–c, for each of the three used magnetizing field-slopes.

4. Discussion

As the curves in Fig. 2 show, there is very little influence of the varied magnetizing field-slope from 0.8 till 51.2 kA/m/s (i.e. 64 times larger speed of magnetization) on sensitivity of the best f_{ij}-degradation functions within their regions of monotonous *increase* (i.e. in the two "whitest" areas of the sensitivity map) see plots (a) and (b) in Fig. 2. However, the best degradation functions from the "blackest" region of Fig. 1, i.e. those with a monotonous *decrease* of the f_{ij}-degradation functions (and/or of the monotonous *increase* of the $1/f_{ij}$-degradation functions, which—being more suitable for practical use—are plotted in Fig. 2c) are influenced substantially. As the degradation functions are created by the signals ratio as shown in Eq. (2), explanation of this behavior can be found through a closer look at the recorded induced voltage signals both for the degraded samples, ε_k, and for

Table 1
Ring-shaped samples of plastically deformed low-carbon steel.

Sample	R23	R20	R17	R18	R13	R7	R2
Strain (%)	0	1.7	3.5	5.8	7.8	12.9	17.9