Journal of Magnetism and Magnetic Materials 402 (2016) 172–177

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

New parameters in adaptive testing of ferromagnetic materials utilizing magnetic Barkhausen noise

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A R T I C L E I N F O

Article history:
Received 13 April 2015
Received in revised form
15 October 2015
Accepted 22 November 2015
Available online 23 November 2015

Keywords:
Magnetic Barkhausen noise
Plastic deformation
Magnetic adaptive testing

A B S T R A C T

A new method of magnetic Barkhausen noise (MBN) measurement and optimization of the measured data processing with respect to non-destructive evaluation of ferromagnetic materials was tested. Using this method we tried to found, if it is possible to enhance sensitivity and stability of measurement results by replacing the traditional MBN parameter (root mean square) with some new parameter. In the tested method, a complex set of the MBN from minor hysteresis loops is measured. Afterward, the MBN data are collected into suitably designed matrices and optimal parameters of MBN with respect to maximum sensitivity to the evaluated variable are searched. The method was verified on plastically deformed steel samples. It was shown that the proposed measuring method and measured data processing bring an improvement of the sensitivity to the evaluated variable when comparing with measuring traditional MBN parameter. Moreover, we found a parameter of MBN, which is highly resistant to the changes of applied field amplitude and at the same time it is noticeably more sensitive to the evaluated variable.

1. Introduction

The magnetic Barkhausen noise (MBN) measurement methods are widely used as nondestructive evaluation techniques for the inspection of materials, as they provide good sensitivity to residual stresses and changes in microstructure of ferromagnetic materials [1–6]. The MBN is caused by the discontinuous motion of magnetic domain walls and discontinuous rotation of moments within domains under external magnetic field. It can be detected by a sensing coil. The detected signal is highly influenced by the frequency of the excitation magnetic field [7,8]. In practice, MBN is measured at the frequencies below 0.1 Hz [9–11] up to above 100 Hz [12]. Measuring at higher frequencies of the excitation field usually provides several advantages, such as a higher magnitude of MBN [13,14], faster measurement, and lower data processing time.

The influence of structural changes and material properties on MBN in general varies throughout the magnetization process; thus the parameters of MBN are, besides the frequency, dependent on the amplitude of the magnetic field [15]. MBN is usually generated using a yoke exciting the sample to saturation. However, sometimes it is advantageous to evaluate the MBN at smaller fields. Thus, a question arises at what field amplitudes MBN should be measured, if we want to carry out MBN measurements in a comprehensive way, for example for later evaluation when the samples are already not accessible. Moreover, the application of MBN method for in-situ measurements of structural changes of steels relies on the optimization of the sensitivity to structural changes, which includes the selection of an optimum magnetic field amplitude.

In the paper [16], we proposed to collect the measurements of MBN with stepwise increased amplitude of the magnetic field into suitably designed matrices. The elements of the matrices in this method are the sensitivities of an investigated parameter of MBN to a structural change. Rows and columns of the matrices represent the applied field and the field amplitude, respectively. As an investigated parameter, the envelope of MBN was chosen in [16]. This method is called here the adaptive MBN method. It employs an approach similar to the method of Magnetic Adaptive Testing (MAT) [17], which is based on the measurement of properly chosen parameters obtained from a set of minor hysteresis loops measured at defined (piecewise linear) exciting field with constant field rate. Thus, each minor loop is measured at different frequencies. The measured waveforms are discretized with the aim of obtaining a large set of properly chosen parameter values at various operating points (e.g. differential permeability, etc., usually appearing to be extremely sensitive to microstructural changes). The differential permeability is thus a function of two parameters – discretized value of instantaneous exciting field and the amplitude of each particular hysteresis loop. The values of e.g. differential permeability obtained at known applied load affecting the microstructure (such as e.g. artificial ageing by means of defined thermal treatment, cold-rolling, neutron irradiation, etc.) are

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http://dx.doi.org/10.1016/j.jmmm.2015.11.064
0304-8853/

organized into a two-dimensional triangular matrix. After applying further defined load, another matrix is obtained and the changes of individual matrix elements are evaluated with the aim of finding the regions of the matrices most sensitive to applied load.

On contrary, traditional magnetic hysteresis methods utilize the measurement of a few major loop parameters, such as coercive field, remanent flux density or maximum permeability, etc. [18]. These parameters are very well suited for the characterization of magnetic properties of ferromagnetic materials, but they are usually not optimized for the assessment of structural changes of materials. On the other hand, MAT and adaptive MBN methods yield parameters (e.g., differential permeability) of several minor loops, from which we can choose the parameter that is the most sensitive to the investigated property change and thus we can easily adapt the method to the particular investigated material and property [17].

In this paper, adaptive MBN method was tested as a tool for the evaluation of plastic deformation of low-carbon steel samples. The parameters of MBN were measured in a clearly monotonous region of the dependence on the structural change, such that the calculation of the sensitivity to this change was simple. We studied the MBN parameters of the steel samples not examined in [16] the power spectrum, the amplitude distribution and the pulse density. The parameters were assembled into matrices, in which the applied field row, originally used in the MAT, was replaced either by a voltage row or a frequency row. The most sensitive parameters of MBN were searched for and the possibility of the application of this method in practical situations will be discussed.

2. Parameters of MBN

The parameters frequently used to interpret MBN were calculated from the signals gathered by the adaptive MBN method. All these parameters of MBN were then averaged over 10 magnetization cycles. The root mean square (RMS) value of MBN is the most commonly measured parameter of MBN. It was evaluated here only for comparing this traditional parameter with the parameters obtained by the adaptive MBN method.

The next parameter obtained from MBN is the power spectrum, which provides the information about the magnitudes of frequency components of the signal. In order to evaluate the sensitivity to the investigated structural change, it was proposed to assembly the S-matrices from the calculated power spectra of MBN, with elements s_{ij} corresponding to the row-column (f_i, h_{Mj}) -pairs, where f_i is the i-th frequency and h_{Mj} is the j-th field amplitude.

Further, the amplitude distribution was gathered from MBN. The amplitude distribution was calculated as a histogram of the relative frequency at which different values of MBN occur. Amplitude distributions were assembled into the A-matrices, with elements a_{ij} corresponding to the (v_i, h_{Mj})-pairs, where v_i is the i-th MBN voltage level.

The final investigated parameter was the pulse density, which represents the relative number of pulses (Barkhausen jumps clustered into avalanches) with the height above a threshold and which was calculated as follows

$$D = \frac{n_h}{n_a} \quad (1)$$

where n_a is the number of all the pulses above the background noise and n_h is the number of pulses above a threshold. Pulse densities were assembled into the D-matrices, with elements d_{ij} corresponding to the (u_i, h_{Mj})-pairs, where u_i is the i-th threshold level.

3. Experimental results

The system designed for testing the proposed method of the MBN measurement is described in [16]. MBN was measured by a sensor coil wound directly around the sample, while another coil wound over it was used to magnetize the sample. The field values were calculated from the measured magnetizing current. We applied a triangular current into the magnetizing coil to obtain a triangular waveform field with stepwise increasing amplitudes. A constant field rate of ± 4 kA/m/s was used at all field amplitudes. Note that other field rates can be tested as well for the data acquisition and signal processing optimization purposes. MBN was amplified and filtered from the signal of the sensing coil using an analog band-pass filter with cut-off frequencies of 1 kHz and 100 kHz and then fed to a data acquisition card. The low-frequency interference component of the sensing coil voltage was additionally eliminated using the digital fifth-order Butterworth high-pass filter.

The adaptive MBN method was tested on window-shaped samples of a commercial low-carbon steel with the composition (C=0.03, Mn=0.19, Si=0.13, P=0.027, S=0.027, N=0.007 wt%) and various plastic deformation state (tensile strain ε=3%, 6%, 9%, 12% and 26%) [19]. Typical power spectra and amplitude distributions for the triangular field with constant field amplitude are shown in Figs. 1–2. Examples of the pulse density in a higher voltage region measured at a field amplitude of 500 A/m are shown in Fig. 3.

The initial field amplitude h_{M1}, maximum value of the amplitude h_{Mm} and step of the amplitude Δh_M used in all the measurements were 200 A/m, 1 kA/m and 100 A/m, respectively. The data files of recorded measurements were processed by a data-evaluation program written in Octave numerical computing environment, which extracted the parameters of MBN from files as a function of the field h_M to evaluate the sensitivity of MBN to the structural parameter (strain). The program interpolated the MBN parameters into S, A and D-matrices with the frequency and voltage step of 4 kHz and 10 mV, respectively. The relative sensitivities of the $s_{ij}(\varepsilon)$, $a_{ij}(\varepsilon)$ and $d_{ij}(\varepsilon)$ elements in 3D plots are presented in Figs. 4–6.

We also compared the optimum a_{ij} and d_{ij} elements obtained after adapting the method to the investigated material and property with the RMS value of MBN. The reciprocal strain dependencies of the most sensitive a_{ij} and d_{ij} elements, as well as the

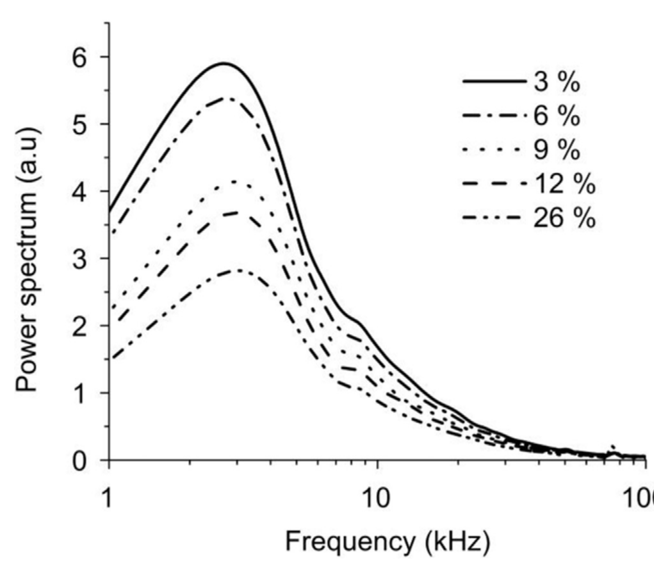

Fig. 1. Power spectrum of MBN for various strains of the low-carbon steel obtained at a field amplitude of 500 A/m.