INFLUENCE OF LIFT OFF EFFECTS ON MAGNETIC BARKHAUSEN NOISE MEASUREMENTS PERFORMED WITH A COMPACT SENSOR UNIT

Boštjan Pečnik¹, Roman Šturm², Janez Grum²*

¹LPKF Laser & Electronics d.o.o., Polica 33, SI-4202 Naklo, Slovenija
²Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva 6, 1000 Ljubljana, Slovenia
*Corresponding author: e-mail: janez.grum@fs.uni-lj.si

ABSTRACT

The aim of the research was to detect and quantify the lift off effects on the captured and processed voltage signals with a compact sensor unit, which will allow the use of uniform criteria for assessing the characteristic properties of the material regardless of the test site. The magnetic method is based on the Barkhausen noise where the proposed correlations allow direct and non-destructive determination of Fe360-B material properties in different cold-deformed states. To avoid edge measurement effects we have provided at least 6 mm distance of compact sensor unit from the edge.

Key words: Non-destructive testing, Barkhausen noise, Lift off effect, Compact sensor unit

1. Introduction

The first experimental confirmation of the existence of magnetic domains was provided in 1919 by Professor Barkhausen. In magnetisation of ferromagnetic materials, changes in the direction of the Weiss domains occur in shocks, which produce with the increase in field intensity, a step-like increase in magnetic flux density in the material. The increase in magnetic flux induces voltage shocks in the measuring coil. The magnetic method based on the Barkhausen noise (BN) permits, among other things, non-destructive testing of various properties of materials such as influences of grain size, microstructure, hardness, degree of cold deformation, and density of dislocations. Swartzendruber and Hicho (1993) [1] and Dobmann et al. (2004) [2] studied specimens with different carbon contents, which were cold-rolled. Capturing of the voltage signals was accomplished prior to and after soft annealing of the specimens with different sensor
units. Langman (1987) [3] and Jiles (1988) [4] conducted investigations on specimens subjected to various mechanical loads and proved relationships between hysteresis loops and BN voltage signals from the specimens showing different residual and loading stresses. A sensor unit makes it possible to capture the so-called voltage signal of the magnetic BN that represents mapping of the individual characteristics of the material microstructure. Bender (1997) [5] has developed miniaturized Barkhausen noise sensors for characterization of magnetic and mechanical properties of ferromagnetic materials, e.g. thin films. The frequency-dependent influence of the probe on the transmitted signals can be determined by the transfer function derived from a model of a ferrite ring head respecting the frequency-dependent complex permeability. Altpeter et al. (1997) [6] have showed that this micromagnetic technique is mainly sensitive to microstructure and residual stress states. Rabung et al. (2014) [7] have showed that micro-magnetic measurement techniques based on the tensile loading dependent maximum Barkhausen noise amplitude can be used for the analysis of micro residual stresses of III kind without the need for a reference method such as the X-ray measurement.

The results of Grum and Pečnik (2006) [8] compare a classical sensor unit having the magnetising and detecting sections separated with a compact sensor unit. A comparison was made on the results of the calibration curves obtained with a compact sensor unit having an additional ferrite core and a detection section integrated as well in the magnetic yoke. Pal’a and others (2010) [9] measured the BN in no oriented Fe–3%Si steel with different average grain sizes. Air gaps between the yoke and the measured objects were also varied during the measurements. The rise of the gap size degraded the level of the BN and caused that the parameters of the BN, such as the amplitude of the BN’s envelope, decreased. Several conditions should be met to make this method applicable especially the level of the BN should be essentially higher than the level of the disturbing noise. Researchers Desvaux and others (2005) [10] performed voltage signal measurements BN in a ferromagnetic material specimens at different frequency ranges of band-pass filter as well as the influence of different penetration depth of the test material.

2. Compact sensor unit

Compact sensor unit contains active magnetizing yoke and integrated ferrite core with winding which provides a unique collection of induced voltage signal of BN. Compact sensor unit has integrated ferrite core, material 12G, with 50 coils of 0.04 mm thick copper wire (Figure 1a). Ferrite core with winding has not a linear relationship between magnetic flux density and magnetic field strength as a measuring coil, because of permeability characteristics of ferrite core itself. The characteristics of the integrated ferrite core are presented in Table 1. Integrated ferrite core 12G acts as a natural amplifier for surface movement of magnetic domains caused by an external alternating magnetic field, which is reflected by the induction voltage measuring coil with a ferrite core. Conductive ferrite core allows us to capture the changing secondary magnetic field caused by the rearrangement of magnetic domains due to the primary magnetic field. Measurements of the physical properties of the material 12G were carried out on core-ring [11]. The relationship between the magnetic flux density B of the magnetic field strength H, B = B(H), was determined before mounting the ferrite core in a given sensor unit. Magnetic field strength is
proportional to the current in the coil winding \( H \propto iN \) which causes the magnetic field. The usefulness of the ferrite material has been proved by permeability measurement in the temperature range between +15 °C and +70 °C (Figure 1b).

Table 1: Characteristics of the integrated ferrite core, material 12G.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tags, units</th>
<th>Measuring conditions</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial permeability</td>
<td>( \mu_i )</td>
<td>10 kHz, 25 °C, 0.1 mT</td>
<td>10,000 ±20 %</td>
</tr>
<tr>
<td>Hysteresis material constant</td>
<td>( \eta_B )</td>
<td>10 kHz, 25 °C, 1.5-3.0 mT</td>
<td>&lt; 1.4</td>
</tr>
<tr>
<td>Saturation magnetization</td>
<td>( B_s ) mT</td>
<td>10 kHz, 25 °C, 250 A/m</td>
<td>≥ 390</td>
</tr>
<tr>
<td>Saturation magnetization</td>
<td>( B_s ) mT</td>
<td>10 kHz, 100 °C, 250 A/m</td>
<td>≥ 280</td>
</tr>
<tr>
<td>Specific resistivity</td>
<td>( \rho ) ( \Omega m )</td>
<td>DC, 25 °C</td>
<td>≈ 0.1</td>
</tr>
<tr>
<td>Curie temperature</td>
<td>( T_c ) °C</td>
<td></td>
<td>≥ 130</td>
</tr>
<tr>
<td>Density</td>
<td>( \rho_s ) kg/m(^3)</td>
<td></td>
<td>≈ 4,900</td>
</tr>
</tbody>
</table>

Fig. 1: Compact sensor unit with integrated ferrite core (a), Incremental permeability of material 12G (b).

Relative loss factor \( tg\delta/\mu_i \) is influenced by hysteresis loss, eddy current loss and residual resistive losses. The resistive losses of the ferrite core effect on reducing the phase angle \( \delta \) between voltage and current. The phase angle is named an angle loss. The impedance of the coil \( Z \) is calculated by the following equation \( Z=R_s+j\omega L_s \), where \( R_s \) is resistive loss of ferrite core (lossless of the winding coil) and \( L_s \) inductive loss. Figure 2 shows the influence of excitation frequency to the relative loss factor \( tg\delta/\mu_i \) of ferrite material at a temperature \( T = 25 \) °C, and to the magnetic flux density \( B = 0.1 \) mT. The relative loss factor of the ferrite material increases logarithmically with a magnetizing as a function of excitation frequency of magnetic field.

In a laboratory experiment a relatively low frequency of 10 kHz excitation magnetic field is used, which is 1000 times less than the smallest value of the relative loss factor. Therefore, we can conclude that in this case the magnetization of material specimen with compact sensor unit with integrated ferrite core at low excitation frequency of the magnetic field \( f = 10 \) Hz and ambient temperature \( T = 25°C \) a relative loss factor \( tg\delta/\mu_i \) is negligible. This means that the
density of the magnetic field of the ferrite core is very little disrupting, and independent of the ferrite material 12G.

Fig. 2: The relative loss factor $\frac{\tan \delta}{\mu_i}$ of material 12G versus excitation frequency.

3. Capturing of Barkhausen noise signal and calibration curves

For the processing and analysis of the BN voltage signal we have selected the excitation and analysing frequencies as $f_{ex} = 10$ Hz and $f_a = 50$ kHz respectively, at a current of 0.5 A. Figure 3 shows capturing of an induced voltage signal in one and a half period. Thus BN voltage signals occurring with a negative slope of a magnetisation curve in the vicinity of the transition at the X-axis (time) were selected for the analysis. The highest amplitude of the BN voltage signal was attained with the most distinctive changes in magnetic flux density.

Analyses of the captured voltage signals were made in terms of four characteristics, i.e.: maximum amplitude, $V_{rms}$ value, power, and variance.

$V_{rms}$ value of the voltage signal is defined as follows in Eq. 1:

$$V_{rms} = \sqrt{\frac{1}{N} \sum_{i=1}^{N-1} x(t_i)^2} = \sqrt{\frac{1}{N} \sum_{i=1}^{N-1} V_i^2}$$  \hspace{1cm} (1)

$x(t_i) = V_i$  \hspace{1cm} discrete points of the BN voltage signal

Power voltage signal is calculated from the power of the individual components by integrating over the entire frequency interval (Eq. 2).

$$P = \int_{-\infty}^{\infty} S_{xx}(f) df = \int_{-\infty}^{\infty} S_{xx}(\omega) \frac{d\omega}{2\pi}$$  \hspace{1cm} (2)

Variance of BN voltage signal for a discrete variable is determined by Eq. 3:

$$S_x^2 = R_{xx}(\tau = 0) = \frac{1}{N} \sum_{i=1}^{N-r} [x(t_i) - <x(t_i)>]^2.$$  \hspace{1cm} (3)

$<x(t_i)>$ represents the mean value of the sample for discrete variable of voltage signal $x(t_i)$:
\[ <x(t_i)> = \frac{1}{N} \sum_{i=1}^{N} x_i. \] (4)

For these reasons the so-called calibration curves were done in the dependence of the degree of cold deformation of the specimen. The slopes of the approximation curves obtained with the compact sensor units are satisfied steep.

4. The lift off impact on the voltage signal estimators

Capturing voltage signal of BN with compact sensor unit is of paramount importance to its resting surface of the specimen of ferromagnetic material. The following are the measurements of voltage signals contained BN, depending on the lift off i.e. size of the gap between the compact sensor unit with integrated ferrite core and the surface of the material specimen of steel Fe360-B. Specimen thickness of a thin sheet, soft state at 0% rate of cold deformation is 3.5 mm. In this research we want to find out the maximum lift off, i.e. the maximum gap between the measuring coil and the surface of the specimen that still provides adequate recording voltage signals of BN (Fig. 1a).

Figure 4 shows the effects of gap on voltage signal of BN, power voltage signal, a time delay, variance of the voltage signal, \( V_{rms} \) value of the voltage signal, the number of peaks, and ratio of \( \Delta V/\Delta t \). For the measurements we have used the sensor lift off from 0 mm to 0.3 mm with step increase in the gap of 0.1 mm. The gap \( \delta = 0 \) mm represents correct and desirable state of sensor unit swept area to capture a subject voltage signal. Frequency distribution of power spectrum of the BN voltage signal markedly differs by the gap size. From power spectrum can be seen that the power of the BN voltage signal weakens with increasing of the gap size. The damping of the autocorrelation curves at the gap sizes 0.0 mm is much weaker than at the larger gap size. Autocorrelation curves are characteristic different at the initial value of the time interval, which represents the variance of the BN voltage signal. Magnetizing parameters were as follows: magnetizing current 0.5A, excitation frequency 10 Hz, sampling frequency 50 kHz, band transmission frequencies between 700 Hz and 200 kHz.
By increasing the gap, the maximum amplitude of the voltage signal of the BN decreases. The largest peak of voltage signal is lowered due to scattering of magnetic field, which reflects in the poor response of magnetic domains in the crystal structure of the material. Visual assessment of typical voltage signals indicates that the compact sensor unit with integrated ferrite core produces characteristic form of the voltage signal up to gap size of 0.2 mm.

Fig. 4: Effect of the gap size from 0.0 mm to 0.3 mm in the BN voltage signals.

The diagrams in Figure 5 shows three curves for different magnetizing currents by 0.5 A, 1.0 A and 1.5 A due to size of the gap. Increasing the magnetizing current increases the voltage level of peaks in the voltage signal of the BN. This is clearly evident in the diagrams of power voltage signal, variance of the voltage signal, \( V_{\text{rms}} \) value of the voltage signal and the maximum voltage changes in a specified time interval \( \Delta V/\Delta t \) as a function of the size of the gap. Estimators, such as the number of voltage signal peaks \( N/\Delta t \) and the time delay, does not give evident differences depending on the gap size. So we assume that the estimator is not suitable for assessing the impact of the size of the gap between the compact sensor unit and surface of the specimen. Diagrams in Figure 5 show the trend of decreasing values of the estimators with increasing size of the gap, independently of the magnetizing current. It is evident that there is a significant difference of the estimators with respect to the gap size of 0.2 mm, which confirms the preliminary findings, carried out on the basis of estimation of voltage signals of BN shown in Figure 4. Based on the individual estimators, such as power voltage signal, variance of the voltage signal, the value of \( V_{\text{rms}} \) voltage signal, and the voltage of the most distinctive changes in a specified time interval \( \Delta V/\Delta t \), we can conclude that the compact sensor unit with integrated
ferrite core, is accurate for material Fe360-B, if the gap is less than 0.2 mm. In Figure 3 is presented also the definition of the ratio estimator $\Delta V/\Delta t = (V_{\text{max}} - V_{\text{min}}) / \Delta t$ and the number of peaks in time interval $N/\Delta t = \text{No.of peaks} / \Delta t$.

Fig. 5: The impact of the gap on the estimator of the voltage signal.

5. Conclusions

The results of the research confirm the usefulness of micromagnetic non-destructive method for the material assessment. The proper selection of the detection coil with ferrite core is very important, as all the other magnetizing parameters. For a proper analysis it is necessary to choose a unique time frame of voltage signal. The estimator requires proper processing and final
evaluation of the results of the calibration curve with the highest correlation coefficient for a
given material.
The results showed that the most distinct voltage signals with the strongest outbreaks were
provided by the compact sensor unit with a magnetising current of 0.5 A. For the processing and
analysis of the Barkhausen noise voltage signal the selected excitation and analysing frequencies,
i.e., $f_{ex} = 10$ Hz and $f_a = 50$ kHz respectively, are the most important.
We can conclude that the selection of a suitable material ferrite core 12G in compact sensor unit
and the low frequency excitation magnetic field $f = 10$ Hz and room temperature provide a
negligible factor relative losses. The proper choice of the material of ferrite core ensures the
smooth transition of the magnetic field thru it and consequently we obtain undistorted
measurements of the Barkhausen noise voltage signal. Judging from the presented results in the
given conditions of magnetization and capturing of the Barkhausen noise voltage signal can be
concluded, that in the case when the lift off is greater than or equal to 0.2 mm, the impact of lift
off on the voltage signal estimator is unacceptable as it drastically decreases the significance of
the estimators for the evaluation of the material specimen.

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