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COMMUNICATIONS

Determination of magnetic field intensity on open sample

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The work is focused on the refinement of the determination of the magnetic field intensity in a Charpy-shaped steel sample. When measuring on an open sample, the intensity of the magnetic field cannot be determined directly from the current by the magnetizing winding. The distribution of the magnetic field around the sample was determined by numerical simulation, the dependence of its intensity on the distance from the sample surface is fitted with sufficient accuracy by a polynomial of the 3rd degree. A system of sensors sensing the distribution of the field at selected points above the sample was designed; by extrapolation using said fitting function, the intensity of the magnetic field on the surface of the examined sample is determined.

Keywords: magnetic field intensity, polynomial approximation, non-destructive defectoscopy, Barkhausen noise

1 Introduction

The described solution is a part of a system for measurement of the magnetic parameters of ferromagnetic structural steels with a focus on Barkhausen noise. The aim of the measurements is to find a correlation between the structural properties of steel obtained by other (destructive) testing methods and non-destructive testing through their selected magnetic parameters.

However, the necessary condition for reproducible measurement is the defined excitation of the measured sample and thus the correct determination of the intensity of the magnetic field in the sample, for example when searching for the parameters of the Barkhausen noise model [1]. The intensity of the magnetic field is one of the parameters that affect the parameters of the measured noise [2], [3].

Destructive tests are often performed on Charpy-shaped steel samples (block $10 \times 10 \times 55$ mm), which is a practically standard shape in the given area. In this paper, we focus on the issue of defined excitation of an open Charpy-shaped sample and on the determination of the field intensity in the surface layer of the investigated material.

2 Problem analysis

From the point of view of magnetization, closed-type sample, especially of toroidal shape is the best, Fig. 1. In this case, the intensity of the magnetic field is directly proportional to the current through the excitation winding and can be calculated from Ampere's law.

When, in addition, $(r_2 - r_1) \ll r_1$, then the intensity of the magnetic field in the sample volume can be considered constant and its value is approximately $H = Ni/(2\pi r_a)$ where $r_a = (r_1 + r_2)/2$ is the mean radius. However, in the case of measurements on a Charpy-shaped sample, it is necessary to close the magnetic flux path with a magnetizing yoke. In Fig. 2(a) there is illustrated an arrangement of the yoke and the sample, the dimensions of the individual components are in Fig. 2b.

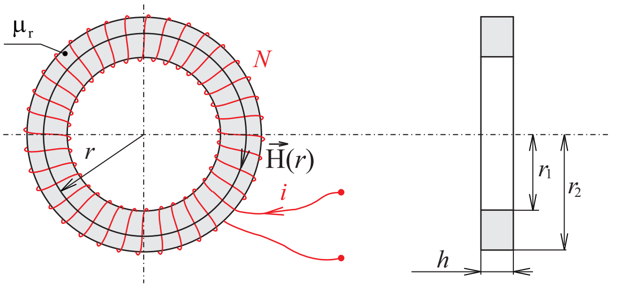

Fig. 1. Closed ring-sample

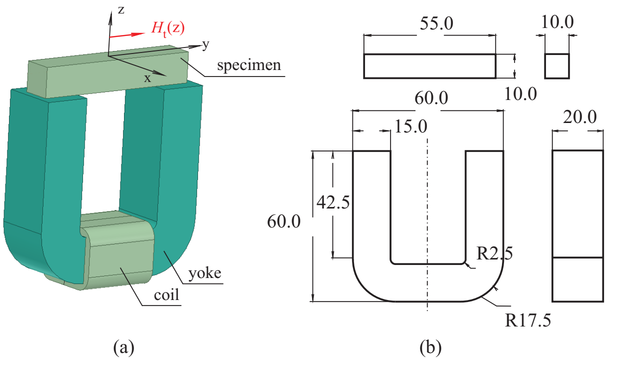

Fig. 2. Magnetic circuit: (a) – geometry, (b) – dimensions

In addition to the sample, the magnetic flux also passes through the magnetizing yoke, as well as through air gaps

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always present between the yoke and the sample. These gaps are, in general, unpredictable and non-reproducible and they noticeably affect the obtained Barkhausen noise [4]. Model of that magnetic circuit is in Fig. 3.

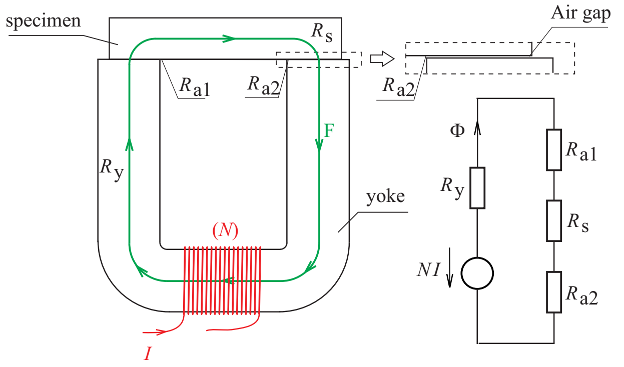

Fig. 3. Model of the magnetic circuit

Magnetic flux can be described by an equation according to Hopkinson's law $\Phi R = NI$, where NI is the magnetomotive force generated by driving coil of N turns, and R is the total reluctance given by a formula

$$R = R_y + R_s + R_{a1} + R_{a2}, \tag{1}$$

where, R_y, R_s, R_{a1}, and R_{a2} are the reluctances of yoke, specimen, and the airgaps, respectively.

In the middle of the sample between the pole pieces, the magnetic flux can be considered approximately homogeneously distributed through the sample, the intensity of the magnetic field given by the expression

$$H = \frac{NI}{\mu S\left(R_{ms} + R_{my} + R_{mg1} + R_{mg2}\right)}, \tag{2}$$

where μ – is magnetic permeability of the sample and S is its cross-sectional area. Although using appropriate dimensions of the yoke and used material it is possible to achieve $R_{my} \ll R_{ms}$, the undefined reluctivity of the air gaps still remains. Moreover the permeability μ of sample is unknown. This means that it is not possible to determine a direct relationship between the intensity of the magnetic field in the sample and the magnetizing current, even with a known arrangement geometry.

The intensity of the magnetic field in the sample can only be determined by indirect measurement - by measuring the intensity of the field in its vicinity. At the interface of materials with different values of magnetic permeability, the tangential component of the magnetic field intensity is preserved. However, this only applies in close proximity ($l_v \ll l_s$), where l_v is the distance from the sample surface, l_s is the sample size within the x axis direction, Fig. 2a. From the point of view of the accuracy of determining the intensity of the magnetic field in the sample, it should be necessary to place the sensor directly on its surface.

The simplest solution is to measure the tangential component of the field with a Hall sensor applied close to the sample surface [4, 5]. The package size of commonly available Hall sensors is at least approximately 3 mm (in SMD design), while the active surface of the sensor can be placed at least approximately 1.5 mm above sample surface, taking into account the supply wires to the sensor. Therefore, a significant error can arise in determining the sample surface field. Refinement can be achieved by using multiple sensors located at different heights above the sample and determining the field strength in the sample by extrapolating the data from such sensors. Several authors chose a pair of sensors [2, 6]. In another case, a pair of sensors was used and an additional shield shaping the magnetic field above the sample surface [7]. In all these cases, the field in the sample was determined by linear extrapolation of the data. However, the width of the Charpy sample is not significantly larger compared to the distance of the sensors from the sample surface, the decrease in field strength with the distance from the sample surface can be relatively non-linear and steep. Linear extrapolation can therefore introduce a significant measurement error.

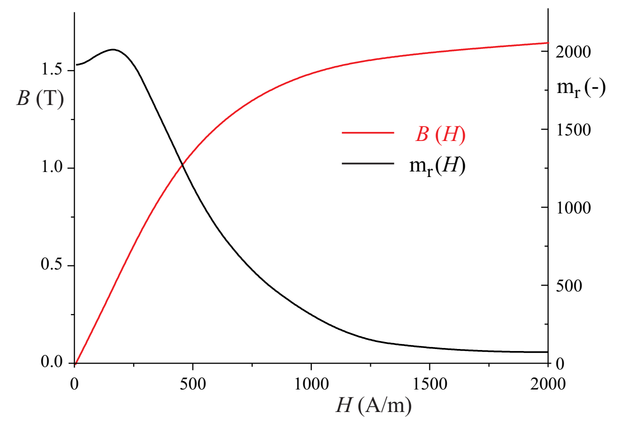

Fig. 4. Initial magnetization path and the dependence of static permeability of steel 12040

The magnetic field above the sample was analysed by the finite element method. The model for the ANSYS program is in Fig. 2(a). A yoke with a constant relative permeability of 1000 was used in the model. Due to higher cross-sectional area of yoke compared to that of sample, its non-linearity was neglected. However, the permeability of the sample can change quite significantly during magnetization cycle, which is illustrated on a measured sample of a plain steel 12040 (carbon content less than 0.4%, manganese content less than 0.8%). Initial magnetization path and the dependence of static permeability $\mu_r = B/(\mu_0 H))$ of this steel is in Fig. 4. The permeability changes between the values of approximately 100 and 2000.

The simulation was performed for sample permeability values of 100, 500, 1000 and 2000. The dependence of the tangential component (with respect to sample surface) of the magnetic field intensity on the distance from the sample surface above its centre $H(0) = H(0,0,z)$ normalized to the value on the surface $H(0) = H(0,0,0)$ is in Fig. 5. The dependencies are nonlinear and their slope changes with permeability. In this figure, the simulation is compared to the measurement. The field intensity was measured at the magnetic field intensity just above the sample of approximately 1000 A/m by a calibrated Gaussmet RFL 912.

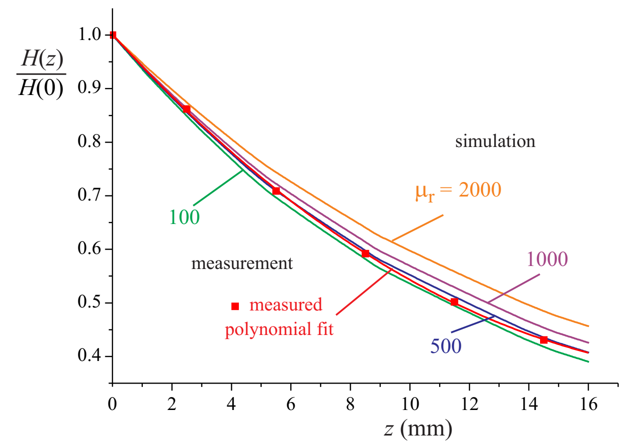

Fig. 5. Dependence of normalised magnetic field intensity on height above sample surface

We found that simulated and measured dependencies can always be well approximated by 3-rd order polynomials

$$H(z) = c_3 z^3 + c_2 z^2 + c_1 z + c_0 . \tag{3}$$

A comparison of the result of simulation and approximation by 3-rd order polynomials is in Tab. 1.

Table 1. Comparison of simulation and polynomial fitting , data in %

μ_r	δ_{avg}	δ_0	δ_{max}
100	0.472	1.746	1.746
500	0.455	1.684	1.684
1000	0.435	0.541	1.201
2000	0.140	0.209	0.503

Here, δ_{avg} is an average relative difference between polynomial fit and simulation over the whole dependence

$$\delta_{avg} = \frac{1}{N} \sum_{i=1}^{N} \frac{|H_{i,fit} - H_{i,sim}|}{H_{i,sim}}, \tag{4}$$

$N = 500$ is a number of points at which simulation and polynomial fit was evaluated. δ_0 is a relative difference between polynomial extrapolation and simulated data at $z = 0$ (specimen surface)

$$\delta_{avg} = \frac{1}{N} \sum_{i=1}^{N} \frac{|H_{i,fit} - H_{i,sim}|}{H_{i,sim}}, \tag{5}$$

and δ_{max}x is a maximum found relative difference between simulation and polynomial fit up to 16 mm above the sample.

3 Sensor design

To unambiguously determine the coefficients of the 3rd degree polynomial, it is necessary to know the values at least at four points above the sample surface. Group of 4 sensors was placed above the sample; the lowest sensor is located as close to the surface as the sensor casing with its terminals allows. Texas Instruments DRV5053 Hall probes with a sensitivity of 90 mV/mT in SOT-23 package of dimensions 2.92 mm × 1.30 mm were used as sensors, Fig. 6.

Let $H_1, \ldots, H_4$ be the values of the magnetic field intensity measured at the points $z_1, \ldots, z_4$ given by the sensor design. Then, the coefficient of approximation polynomial (5) can be determined by the field intensity values at these points using a system of equations

$$\begin{bmatrix} c_3 & c_2 & c_1 & c_0 \end{bmatrix} \cdot \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} = \begin{bmatrix} H_1 \\ H_2 \\ H_3 \\ H_4 \end{bmatrix} . \tag{6}$$

Magnetic field intensity on the sample surface $(z = 0)$ is then given by formula

$$H\Big|_{z=0} = c_0 . \tag{7}$$

Therefore, it is necessary to find only one root of the equations system. Root calculation using determinants is fast and easy to implement (for example in C/C++) even on a relatively simple microcontroller.

The block diagram of the sensors is in Fig. 7. A low-pass filter is connected to the output of each Hall probe (HP1 - HP4) represented by a simple RC element to suppress interfering noise present in signal. Its cut-off frequency is set so as not to distort the useful signal. In our

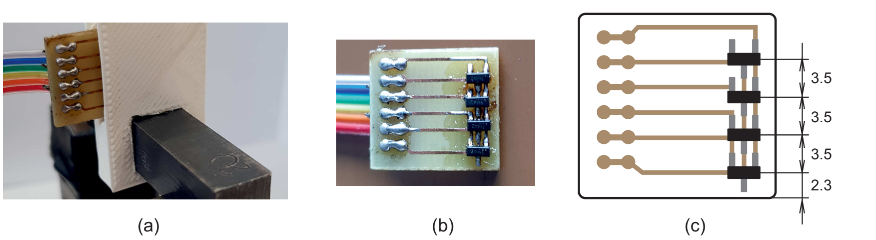

Fig. 6. Sensor: (a) – positon on the sample , (b) – detail of the sensor board , and (c) – layout drawing with dimensions

case, it was set relatively low, as the magnetization characteristics and Barkhausen noise are sensed at a magnetization frequency of max. 5 Hz. The signal from the sensors is processed by the AGILENT U2542 multi-channel synchronous 16 bit A/D converter module.

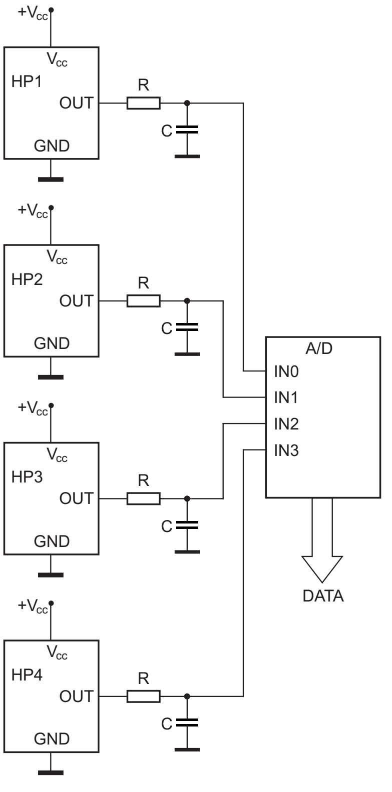

Fig. 7. Block diagram of sensor module

4 Conclusions

An arrangement of sensors for determining the intensity of the magnetic field in a Charpy-shaped sample was designed and implemented. Simulations and measurements have shown that a decrease in the intensity of the magnetic field with a distance above the sample surface can be fitted with sufficient accuracy with a 3^{rd} degree polynomial. Values of the magnetic field intensity obtained by the four Hall probes spaced at defined distances from the sample surface are used to "ad-hoc" determine the approximation polynomial coefficients for each single measurement. Using it, extrapolation with the assumed error in the worst case of about 1.7% determines the value of the magnetic field intensity on the sample surface. Compared to the often used measurement using one sensor, or by linear extrapolation of the values of several sensors, we determine this value more accurately. In the case of a sample of other dimensions, or shape, the sensor can be adapted relatively easily by changing the approximation function.

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