Andrzej WAC-WŁODARCZYK, Tomasz GIŻEWSKI, Ryszard GOLEMAN

Lublin University of Technology

The methodology of magnetic materials classification

***Abstract**. The classification of magnetic materials is a process including the subsumption of distinctive features according to affinity categories. To identify any group one needs to adopt a model whose basic characteristics complies with the changes imposed by structure, geometry, space defects, etc. In the following thesis the authors wish to present the methodology of classifying magnetic materials according to a model analogous to the weight function of the classical Preisach model.*

***Streszczenie.** Klasyfikacja materiałów ferromagnetycznych jest złożonym procesem przyporządkowania określonej grupie obiektów podobnych – o określonej klasie podobieństwa. Do identyfikacji grup zaadoptowano model czuły na istotne zmiany charakterystyk zewnętrznych. Wybrano I przestawiono funkcję wagi modelu Preisacha oraz określa metodologię klasyfikacji badanych materiałów oraz wad materiałów. (**Metodyka klasyfikacji materiałów magnetycznych**)*

Keywords: non-destructive testing, classification, weigh function.
Słowa kluczowe: badania nieniszczące, klasyfikacja, funkcja wagi.

Introduction

The automatic classification of multidimensional objects is a process that requires the adoption of a model that explicitly depicts their basic properties and characteristics [2]. The objects tested for ferromagnetic properties are suitable for examination by means of dynamic methods.
The fundamental method is to determine the eddy-current changes inside the tested sample as a consequence of magnetic field intensity, as well as the frequency values [3]. Essential here is the observation of a trajectory following either the impedance module or impedance argument change. Another method belonging to the inductive way of testing ferromagnetic objects is that which examines the magnetic hysteresis loop. It is an object composed of closed spline, whose shape, as well as the area defined by the, exhibit specific dynamic properties: magnetic permeability, and dynamic losses (including eddy current), etc. The observation of the hysteresis loop comprises the acquisition process of induction changes or magnetisation in a function of magnetic field intensity [3]. The type and the method of measuring do not require any particular solutions in the measuring system. In other words, any method of examination that makes it possible to determine the dynamic dependences $M=f(H)$, with a non-invasive survey of above-mentioned values is acceptable.

The solutions presented in the article are not essential. What is fundamental as far as the analysis of the subject is concerned is the measurement that employs digital signal conditioning methods, indispensable to forming adequate data collection. The process of automatic identification is a specific method of data transformation, its essential element being the figure of input collection. In applying the closed-hysteresis loop, its automatic classification and identification was abandoned, as it does not comply with the functional definition. The search for a multidimensional surface, describing the properties of the sample, led to the application of the Preisach weight function as a static image of ramified characteristics which comprises a magnetic hysteresis loop [7].

The article presents a brief description of the classical Preisach model, as well as the method for acquiring a discrete image of the weight function. Two ways of measurement follow the investigation of the weight function image: an arbitrary one and one employing a matrix. The comparison of both methods will make it possible to assess the possibility of applying the automatic process of defect detection by means of the algorithm described by the authors.

The basic model

The classical Preisach model as a macroscopic model of structure is presented as a parallel summary weighed hysteresis operator $\gamma_{\alpha\beta}$, known also as elementary switching hysteresis.

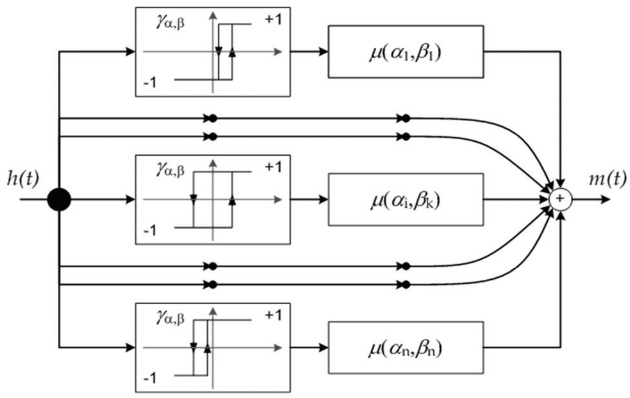

Fig. 1. The block diagram of the Preisach model

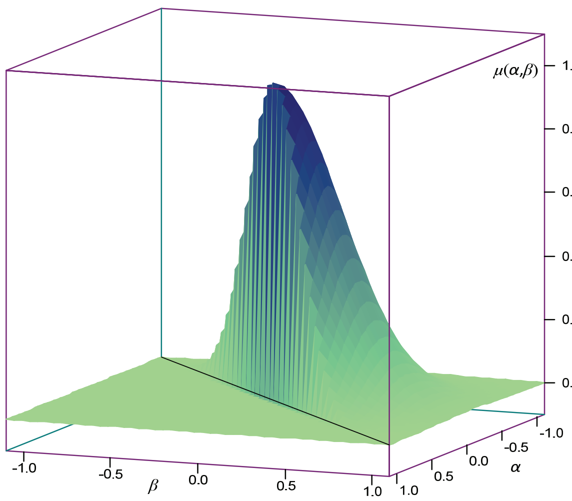

Fig. 2. A graphical presentation of the weight function

Such an approach defines the foundation of the system of hysteresis modelling. The block diagram of the system is presented in Fig. 1. The values represented by the function $\mu(\alpha,\beta)$ determine the $\gamma_{\alpha,\beta}$ operator weight. Each of them is defined for the pair of values α and β, where $\alpha \geq \beta$ [1, 6].

From the mathematical point of view, the operator is defined as a projection of the $\mathbf{R}^2$ collection, with output values of magnetisation $m(t)$, dependent on the historical input values of the magnetic field intensity $h(t)$, as well as linearly dependent on the h α, β parameters.

(1) $$m(t)=\iint\limits_{P}\mu(\alpha,\beta)\gamma_{\alpha\beta}\,\mathrm{d}\alpha\mathrm{d}\beta$$

The behaviour of switching hysteresis - and thereby the Preisach model - is defined for continuous input values $h(t)$. Each of them reacts with the output value according to the input value. The weight sum of all the elementary input operators values determines the total of the system response. The collection of weights $\mu(\alpha,\beta)$ models the weight function μ: P→R (Fig. 2), being defined as a description of relevant proportion of elementary operator to total hysteresis [1, 6, 7].

In order to estimate the value of the weight function $\mu(\alpha,\beta)$, based on experimental data, it is vital to estimate the family of hysteresis first-order reversible loops. Skipping the ways of distinguishing mentioned in the references, the authors offer only the method applied in their own research [6]. The modelling of characteristics $\mu(\alpha,\beta)$ was carried out by means of mathematical analysis, following the definition of the Preisach model (1). The algorithm serves as a means of designating the reverse curve [6, 7].

(2) $$\mu(\alpha',\beta')=-\frac{\partial^2 Y(\alpha'\beta')}{\partial\alpha'\partial\beta'}$$

The dependence defining the weight function is represented by equation (2) [6], where Y is measured by the value in point α', β'.

Experimental research

The methodology of experimental research requires the measurement of two quantities: the current value in the magnetising circuit and the inductive voltage in the measuring coil. The graphical representation of the weight function presented in Fig. 2 shows the results for ferromagnetic objects. The research is conducted by means of a circuit with the possibility of measuring the current in the magnetic circuit, as well as the electromotorical inductive force in the coil, coupled with the magnetising coil by the tested element [3].

The other, more precise method involves measurement employing a matrix: both a differential and a bridge one. In Fig. 3 one can see the draft of a measuring system for alternating a current bridge associated with a magnetic circuit owing to couplings C_L, C_{L1} and C_{L2}. The bridge elements, namely resistors R_1, R_2, R_3, R_4, inductive coils - L_2, and L_4 as well as the voltage source $e(t)$ - have linear parameters in the measuring range. L_1 and L_3 are coils with nonlinear ferromagnetic elements: a matrix and the tested sample.

From the analytical point of view it is appropriate to determine the value whose changes result in the manifestation of unbalanced voltage up. By means of measuring, an essential feature is the element that includes magnetic coupling C_{L1} and C_{L3}. The approximations obtained in the stated equations make it possible to present changes in unbalanced voltage that assume the shape of the equation regarding the complex function of magnetic flux Ψ_1 and Ψ_3, assigned to the matrix and test samples (3).

(3) $$u_P\approx\frac{1}{2}\frac{\mathrm{d}(\Psi_1-\Psi_3)}{\mathrm{d}t}$$

The mathematical model of voltage with amplitude E, pulsation ω and dumping factor τ, represented in equation (4), was generated by means of a multifunctional measuring device. The analogical signal was filtered in order to eliminate noises, which were the effect of digital generation. Having amplified the signal, the magnetic coil circuit was reinforced. The measurement of quantities characteristic of a magnetic field and induction in the tested object was taken according to the principles of magnetic measurements with the help of the inductive method with a coils converter.

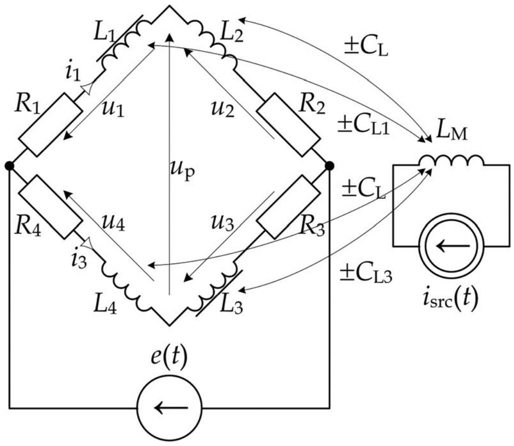

Fig. 3. The scheme of a bridge measuring system

(4) $$e(t)=E\mathrm{e}^{-\tau t}\sin\omega t$$

The data collection includes temporary values for the magnetic current as well as for the inductive tension in the measuring coils. The system of analysis and data acquisition was developed in a way that allows the filtering and integration of the signal in a selected measuring channel. The values of α and β parameters for multidimensional functions are dependent on the process of temporary values of the magnetic field intensity. Owing to the possible ramified points it is convenient to employ magnetic value $M=f(H)$. Such an approach makes it possible to distinguish the immediate impact of hysteresis on the value one is searching for, the increase factor, and the existing extremes (Fig. 2).

Having analysed the tested characteristic as well as formula (2), equations collection was completed, the solution algorithm of which was worked out after having designed weight functions starting with $j=i$ elements, that are located on the bounds of the Preisach triangle (on the line $\alpha=\beta$), then accordingly $j=i$-1, …, $j=i$-n (n stands for the number of quantum intervals). As a result the following algorithm-designating weight function values were obtained (5).

(5) $$m_{i,j}=\frac{Y_{i,j}-Y_{i,j-1}}{2}\left[\sum_{k=j}^{i-l}\sum_{l=j}^{i-1}\mu_{k,l}-\sum_{l=j+1}^{i}\mu_{i,l}\right]$$

(6) $$\mu(\alpha,\beta)=g(-\alpha)g(\beta)$$

All restrictions imposed by the Preisach model have been adopted, which implies that $\mu_{k,l}=0$ for $l<k$ and $\mu_{i,l}=0$ for $l<i$. It is possible to determine the weight function on the basis of the discrete measurement values of B and H with a closed, limited hysteresis loop. On the basis of the relationships (6) a one-dimensional function $g(x)$ can be specified, whose product defines the weight function. From this, you can also define the gradient of the test function $\mu(\alpha,\beta)$.

$$
(7) \qquad \begin{cases} G_{\mathrm{i}} = \dfrac{1}{2\delta} \dfrac{B_{\mathrm{i}+1} - B_{\mathrm{i}}}{H_{\mathrm{i}+1} - H_{\mathrm{i}}} \\ g(H_{\mathrm{i}}) = g_{\mathrm{i}} \end{cases}
$$

By introducing conditions (6) an iterative algorithm is defined for the weighted Preisacha surface. The system allows the determination the surface differential for the various properties of ferromagnetic samples. Due to the outcome some parameters are subject to observation:
- the distance between the extremes of the function,
- the shape of the surface-partial derivatives.

For each tested material and the shape of the sample, the system must be calibrated separately. Hence, it is possible to use relative sizes.

The multidimensional object class

Hysteresis is the basic object of analysis in the problem studied. Most frequently the critical hysteresis loop, or its family, designed for different amplitudes of harmonic magnetic fields, is estimated. However, an explicit classification is problematic owing to the restriction caused by the closed loop. As mentioned before in space $\mathbf{R}^{2,}$ hysteresis is not a function. Consequently, aiming at multidimensional analysis it is convenient to determine the weight function of the Preisach model.

Having considered the methodology of measurement, only two types of static characteristic have been investigated. The first one is the typical weight function (Fig. 2), which was defined in the Preisach triangle domain. Its fundamental properties allow for the automatic classification of the given material. The function defined in space $\mathbf{R}^3$ with its domain in $\mathbf{R}^2$ possesses one maximum at the most (or a maximum value) in the neighborhood of point (0,0).

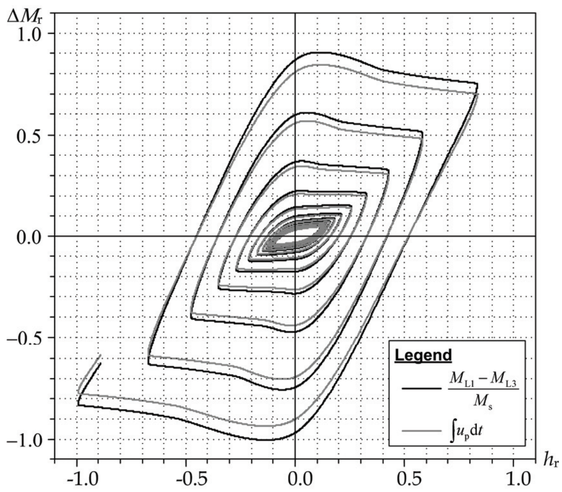

Fig. 4. Differential hysteresis $\Delta M_r=f(h_r)$ according to saturation magnetisation M_s: M_{L1} – magnetisation by means of inducted voltage u_1, M_{L3} – magnetisation by means of inducted voltage u_3, u_p- unbalanced voltage of the bridge

The other image is the weight function obtained by means of measurement conducted with alternating current bridge, through the examination of unbalanced voltage u_p. The conditions of its stability imply that unbalanced voltage u_p equals 0 when the parameters elements are equal in pairs with ferromagnetic elements properties among them. Its nonzero value indicates that the properties of the tested sample and matrix are different. It was observed that transforming the voltage into differential hysteresis (Fig. 4). and then determining the differential weight function (Fig. 5) allows the classification of data collection.

Depending on the algorithm for the identification of classifying surface features, it is possible to obtain a variety of static images. This is a starting point in determining the classification of the basic algorithm. However, due to the limited volume of work, the authors do not take the discussion on the selection of applications grouped in classes of similarity. There remains only the interesting shape of the surface and a selection of the main features.

The weight function as classifying collection

The basic collection determining the ferromagnetic material class was defined as a weight function. It is a characteristic, determined for relative values, normative shape and assigned magnetic field frequency.

For classification purposes, a series of numerical tests and experimental measurements were carried out in order to identify good examples of images of static hysteresis. For a typical ferromagnetic test piece of circular cross-section there were defined static and dynamic hysteresis loops. In this phase of the experiment, the results were analysed qualitatively.

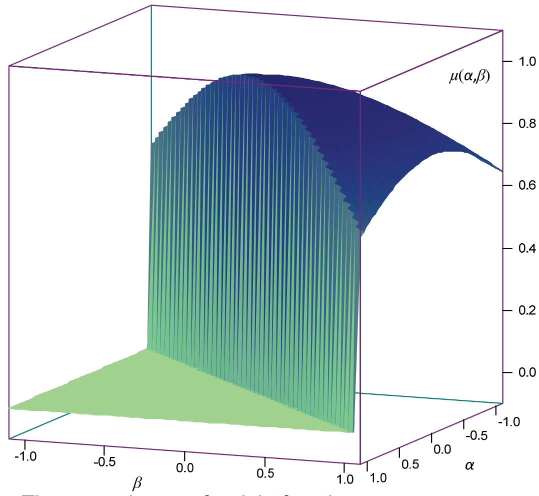

Fig. 5. The second case of weight function

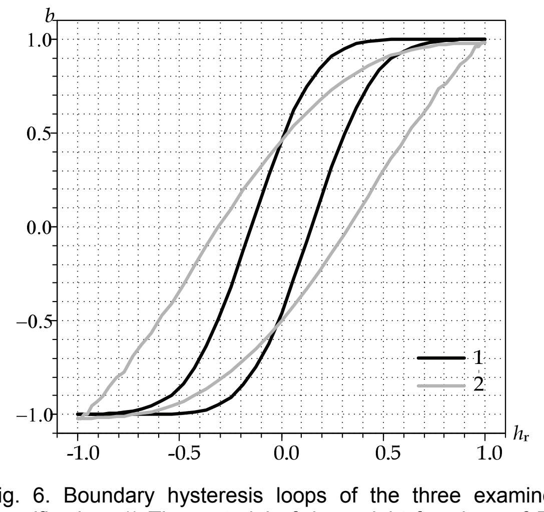

Fig. 6. Boundary hysteresis loops of the three examined case classification: 1) The material of the weight functions of Fig. 2; 2) The material of the weight functions of Fig. 5

Figure 5 shows the weight function of the sample with a boundary hysteresis loop with a larger area, which is limited more by the sloping and the growing one than in the case of Figure 2. Areas have been identified for the same steel rods, one of which was damaged by milling a channel with a depth of 2 mm and a width of 1 mm. Boundary hysteresis loops are shown in Figure 6. The above samples were analysed for the position of the maximum value.

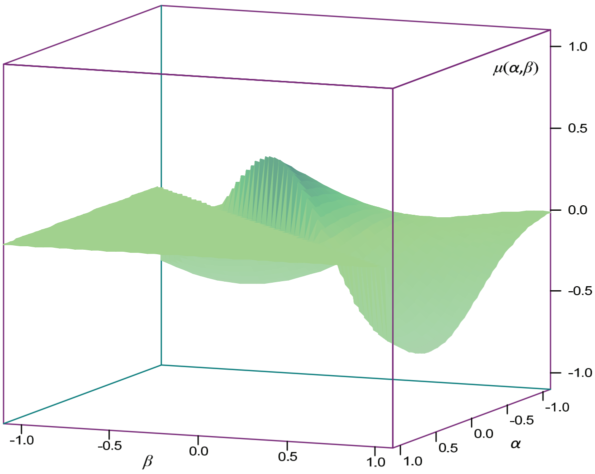

Fig. 7. The Weight function for the difference in material properties of class 1

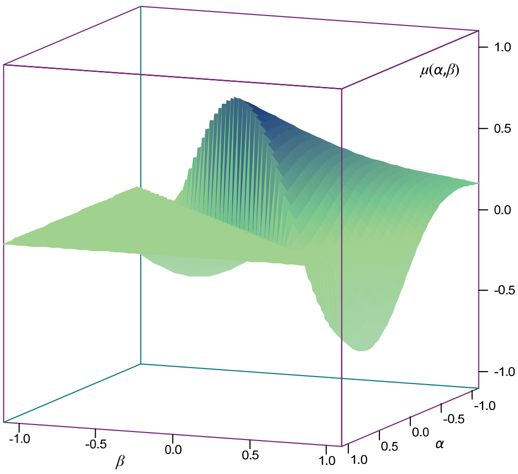

Fig. 8. The Weight function for the difference in material properties of class 3

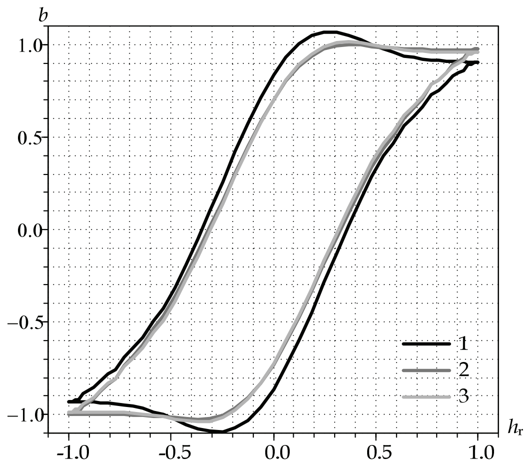

Fig. 9. The boundary hysteresis loop differential for the studied three classes of weight functions

The appearance of defects according to earlier estimates did not alter the coordinates of a point with the highest value. Only the slope and value of the function at point (0,0) changes. Thus a pattern classifier causes a significant complication in the automatic classification. The study for various configurations of a measurement experiment was conducted. The most important was differential measurement.

Each image of the surface was modelled upon identical measuring values, creating a state of saturation. The experiments were conducted with cylindrical dimentials 10 mm in diameter with transverse defects l=0,1 mm (Fig. 7), l=0,15 mm (Fig. 8). The above-mentioned surface shapes differ from each other by means of the position of their extremes, their values, and an increase in the weight function in the essential, from the point of view of the classification, surfaces. The analysis of the graphical presentation of the weight function (Fig. 7 and Fig. 8) indicates that its differential image is sensitive to the changes in the structure of the material geometry. Considering adequate critical hysteresis loop as well as differential ones (Fig. 8) it was observed that small hysteresis variations are followed by profound differences in the shape of the surfaces of differential weight functions.

In the cases analysed, introducing an application was designed to refine the surface through the analysis of partial derivatives, extrema of the distance, or other characteristic points. It was important for the work to represent the surface derived from experimental studies. These surfaces were subjected to clustering by classifier automatons.

Conclusions

The above-presented considerations apply to the algorithm for assembling information about the image of the weight function and its derivative from the experimental data as well as the method of their application in the classification of magnetic materials. It was perceived that essential features, namely permeability, magnetisation, or generally dynamic hysteresis loop, determine the material class. It is extremely hard to form rules of automatic process on the grounds of the mentioned above properties. The weight function allows the determination of the numerical images of a material or in differential measurement, of faults and defects in the structure of identical details for which formulation of the set of rules allows explicit classification as well as identification by means of automatic process.

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***Authors**:*
dr hab. inż. Andrzej Wac-Włodarczyk, *Politechnika Lubelska, IPEE, ul. Nadbystrzycka 38a, 20-618 Lublin, E-mail: a.wac-wlodarczyk@pollub.pl;*
dr inż. Tomasz Giżewski, *Politechnika Lubelska, IPEE, ul. Nadbystrzycka 38a, 20-618 Lublin, E-mail: t.gizewski@pollub.pl;*
dr inż. Ryszard Goleman, *Politechnika Lubelska, IPEE, ul. Nadbystrzycka 38a, 20-618 Lublin, E-mail: rgoleman@pollub.pl;*