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 comply 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 podobieństw. 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 \( M=\mathcal{F}(H) \), 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 mathematical model of a voltage signal with amplitude $E$, pulsation $\omega$ and damping factor $\tau$, 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](image)

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 $\alpha$ and $\beta$ 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 $M=\mu(H)$. 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 $j=1$ elements, that are located on the bounds of the Preisach triangle (on the line $\alpha=\beta$), then accordingly $j=1, \ldots, j+n (n$ stands for the number of quantum intervals). As a result the following algorithm-designating weight function values were obtained (5).

$$m_{i,j} = \frac{Y_{i,j}-Y_{i,j-1}}{2} \sum_{k,l=1}^{j-1} \mu_{k,l} - \sum_{l=j+1}^{n} \mu_{i,l}$$

(5)

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

(6)

All restrictions imposed by the Preisach model have been adopted, which implies that $\mu_k=0$ for $l<k$ and $\mu_k=0$ for $k<l$. 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 $\mu(\alpha, \beta)$. 

input values of the magnetic field intensity $h(t)$, as well as linearly dependent on the $h \alpha, \beta$ parameters.

$$m(\alpha, \beta) = \int_0^\beta \int_0^\alpha \mu(\alpha, \beta) d\alpha d\beta$$

(1)

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

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

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 $\alpha$ and $\beta$ 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 $M=\mu(H)$. 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).

The mathematical model of a voltage signal with amplitude $E$, pulsation $\omega$ and damping factor $\tau$, 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.

The mathematical model of a voltage signal with amplitude $E$, pulsation $\omega$ and damping factor $\tau$, 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.
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 $\mathbb{R}^2$, 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 $\mathbb{R}^2$ with its domain in $\mathbb{R}^2$ possesses one maximum at the most (or a maximum value) in the neighborhood of point $(0,0)$.

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.

\[
\begin{align*}
G_i & = \frac{1}{2\delta} \frac{B_{i+1} - B_i}{H_{i+1} - H_i} \\
\theta(H_i) & = g_i
\end{align*}
\]

By introducing conditions (6) an iterative algorithm is defined for the weighted Preisach 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.

![Figure 4](image4.png)

Fig. 4. Differential hysteresis $\Delta M = f(h)$ according to saturation magnetisation $M_s$, $M_i$ – magnetisation by means of inducted voltage $u_i$, $u_{uw}$ – 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.

![Figure 5](image5.png)

Fig. 5. The second case of weight function

![Figure 6](image6.png)

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

The material of 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.
Each image of the surface was modelled upon identical measuring values, creating a state of saturation. The experiments were conducted with cylindrical dimenstions 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.

REFERENCES

Authors:
dr hab. inż. Andrzej Wac-Wlodarczyk, Politechnika Lubelska, IPEE, ul. Nadbystrzycka 38a, 20-618 Lublin. E-mail: a.wac-wlodarczyk@pollub.pl;
dr inż. Tomasz Gizewski, 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: r.goleman@pollub.pl;