УДК 681.518.3 DOI: https://doi.org/10.37434/tdnk2022.01.04

AUTOMATED NON-DESTRUCTIVE TESTING OF STEEL ALLOYS MICROSTRUCTURE BASED ON MULTIFREQUENCY EDDY CURRENT METHOD

АВТОМАТИЗОВАНИЙ НЕРУЙНІВНИЙ КОНТРОЛЬ МІКРОСТРУКТУРИ СТАЛЕВИХ СПЛАВІВ НА БАЗІ БАГАТОЧАСТОТНОГО ВИХРОСТРУМОВОГО МЕТОДУ

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The traditional and most common methods for controlling the results of heat treatment of steel alloys are determination of hardness by measuring the parameters of indentation and quantitative and stereometric metallography. These methods are time-consuming in terms of control operations, which are performed according to a special methodology consisting of a visual comparison of the study results with the standard scales, followed by statistical extrapolation to the entire batch or plane of the product. The quality of such operations largely depends on the qualifications of the operators performing them. Presented in this article is the application of an automated open-circuit system of program control of multifrequency eddy current non-destructive testing as an alternative to traditional methods of control of the results of steel alloys heat treatment. It is shown that at certain parameters of programming the measurement operations there is a correspondence between the phase characteristics of the response signal of the 5th harmonic and the type of heat treatment, hardness, and microstructure arrangement in grade 40X steel samples. 28 Ref., 1 Tabl. 1, 5 Fig.

Традиційними та найбільш поширеними методами контролю результатів термічної обробки сталевих сплавів є визначення твердості шляхом вимірювання параметрів відбитка після вдавлювання індентора та кількісна і стереометрична металографія. Ці методи потребують багато часу на здійснення операцій контролю, які виконуються за спеціальною методологією, за якою проводиться візуальне порівняння результатів дослідження зі стандартними шкалами з подальшою статистичною екстраполяцією на всю партію або площину виробу. При цьому якість виконання таких операцій в значній мірі залежить від кваліфікації персоналу, що їх виконує. Представлено застосування автоматизованої розімкненої системи програмного управління багаточастотного вихрострумового неруйнівного контролю як альтернативи до традиційних методів контролю результатів термічної обробки сталевих сплавів. Показано, що при певних параметрах програмування операцій вимірювання спостерігається відповідність між фазовими характеристиками сигналу відгуку 5-ї гармоніки та типом термічної обробки, твердістю, будовою мікроструктури зразків зі сталі марки 40Х. Бібліогр. 28, табл. 1, рис. 5.

Keywords: multifrequency eddy current non-destructive testing, automated open-circuit system, program control, microstructure, thermal treatment
Ключові слова: багаточастотний вихрострумовий неруйнівний контроль, автоматизована розімкнена система, програмне управління, мікроструктура, термічна обробка

Introduction

Until recently, the development of non-destructive testing (NDT) systems has progressed in a self-sufficient way with the main focus on improving the signal-noise ratio performance, artifact control, compliance with a number of industry standards. Thanks to the use of digital signal processing technologies, NDT operations reach the level of application in automated enterprise management systems when NDT result data become the information objects of automated decision-making systems.

One of the new areas of research with regard to digitalization and automation of production processes is the use of NDT methods, primarily electromagnetic [1–4] and ultrasonic [5, 6], to determine the structurally sensitive physical properties of metals and alloys.

The aim of the present study is to analyze the possibility of using automated eddy current NDT to characterize the microstructure of 40X steel alloy after heat treatment. Using this method, it is planned to establish a correspondence between the amplitude-phase-amplitude characteristics (APAC) of the

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polyharmonic eddy current response signal and the type of heat treatment, microstructure, and hardness of a 40X steel sample.

Setting the task. The NDT eddy current method is one of the most widely used methods of non-destructive testing. The principle of its operation is based on tracking, determining and analyzing the interaction of an external source electromagnetic field, which is usually the inductor (one or more) of the eddy current converter (ECC) with the electromagnetic field of eddy currents arising in the object under control (CO) as the result of impact of ECC electromagnetic field on it. Information on the CO is obtained from the distribution of eddy current densities and is determined by ECC design, geometric characteristics and parameters of electrical conductivity and magnetic permeability of the CO material, and spatial position of ECC relative to the CO [7, 8].

Considered as critical for eddy current NDT are such disadvantages as manifestation of eddy currents only in electrically conductive materials, which limits the application of the method for products made of metal alloys or with a carbon content (carbon composites); the lift-off effect of ECC from the surface of the CO, as a result of which artefacts are formed, and it significantly complicates the inspection of CO of complex geometric shape; insignificant depth of penetration of the ECC field into the CO material (surface effect) [7, 8]. The eddy current NDT advantages are the absence of contact of ECC with CO, simplicity of ECC design in certain models (with one or two inductors), lower in comparison with other NDT methods, such as acoustic or opto-acoustic, dependence of signals on temperature and humidity, readiness of the CO surface for testing, safety for humans and animals [7, 8].

Eddy current NDT, as a rule, is used for detection and parameterization of defects, first of all cracks, pores, various inclusions, etc. The set of disadvantages and advantages determines the scope of eddy current NDT. For example, due to its non-contact advantage, the method is used in automated NDT systems, including robotic scanners, which provide high-speed continuous control of products of simple geometric shapes, and the lift-off effect, for example, is the basis for dielectric coating thickness measurement.

Improving the sensitivity of NDT eddy current systems and automating digital processing of response signals have opened a new direction of its application – determining the conformity of the CO structure to the reference or establishing structural heterogeneity of CO material, for example, assessing the quality of mechanical and heat treatment [9–18]. The detection of structurally sensitive parameters of ECC signals and the search for optimal conditions for the excitation process of CO according to the criteria of sensitivity to the level of heat treatment, type of microstructure and hardness of 40X steel samples are presented in this article.

The detection of structurally sensitive parameters of ECC signals and the search for optimal conditions for the excitation process of CO according to the criteria of sensitivity to the level of heat treatment, type of microstructure and hardness of 40X steel samples are presented in this article.

Mechanical, dynamic, and fatigue tests, macro- and microanalysis, chemical methods of phase analysis of steel, electron microscopy and electrography, X-ray microscopy and X-ray diffraction analysis, quantitative and stereometric metallography (statistical methods) for studying the structure of metal alloys have a low level of productivity, require significant funds for the maintenance of expensive and complex equipment, and for some methods require special safety measures, which leads to significant time and financial losses of production processes. Due to the described advantages and progress of eddy current NDT, it becomes an effective alternative to these traditional methods under the condition of correlation between ECC signals and chemical and physical properties of CO material, which is manifested through its electrical conductivity and magnetic permeability.

Main part. Heat treatment of iron-carbon alloys is one of the most common technological operations to change their microstructure [19, 20]. The opera-

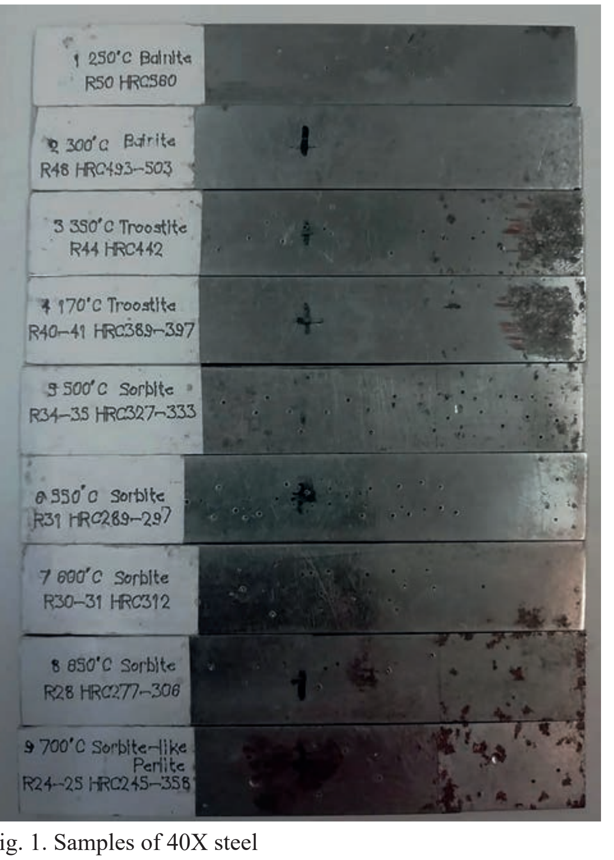

Fig. 1. Samples of 40X steel
Рис. 1. Зразки зі сталі 40X

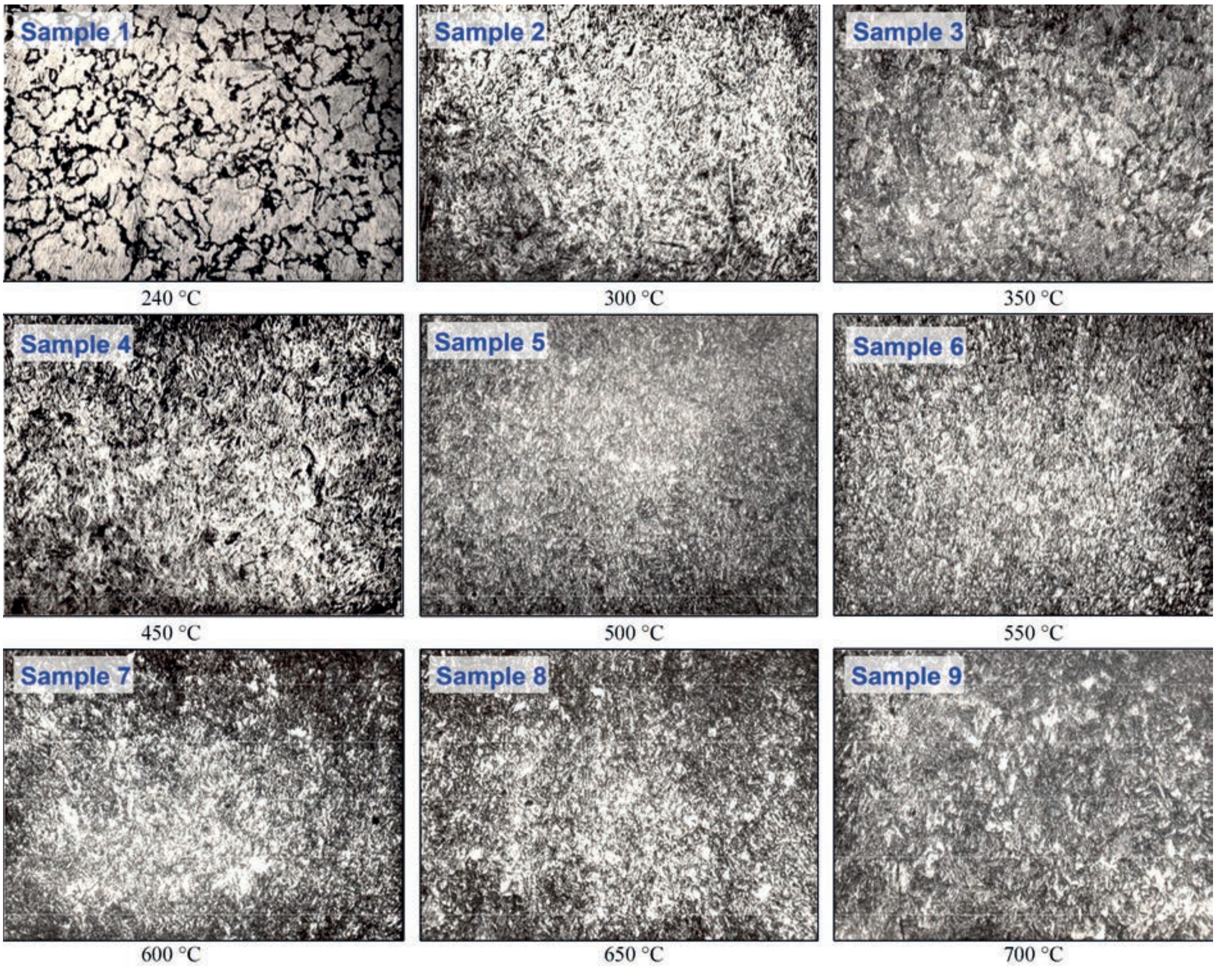

Fig. 2. Pictures of the samples microstructure at different tempering temperatures
Рис. 2. Зображення мікроструктури зразків, відповідне до температури відпуску

tional properties of the products depend on the exact observance of the heat treatment technology.

In our study we used 9 samples (Fig. 1) of steel grade 40X, which were subjected to heat treatment: first, the samples were hardened in one cooler (oil) at 850ºC, followed by tempering with different temperatures to change their microstructure (see table). The results of heat treatment were determined by two methods: measuring the hardness of the Rockwell test on the *HRC* scale (see table) [21, 22] and the method of quantitative metallography (table, Fig. 2) [23].

Tendency in hardness and microstructure changes in correlation with tempering temperature is given in the table here below.

The «Structurescope EG» system of non-destructive testing (NDT), developed and constructed by us, was used, in order to establish a relation between APAC of the eddy current NDT polyharmonic response signal and the type of heat treatment, arrangement of microstructure, and hardness [24]. By the nature of its control algorithm, it belongs to open-circuit systems, by the nature of its signal changes – to program control systems [25, 26]. The block diagram of the system is presented in Fig. 3. The proposed design includes a control unit (*1*), which controls the unit for digital synthesis and signal processing of eddy current NDT (*2*) and a robotic scanner (*3*), which positions ECC (*4*) relative to CO (*5*) along three axes with the accuracy of 100 μm. The ob-

Results of identified properties of the iron-carbon alloy at different tempering temperature
Результати виявлених властивостей сплаву залізо-вуглець при різній температурі відпуску

Sample №	Tempering temperature, °C	Rockwell Hardness, HRC	Identified microstructure
1	240	50	Troostomartensite
2	300	48	Troostomartensite
3	350	44	Troostite
4	450	40...41	Troostite
5	500	34...35	Sorbite
6	550	31	Sorbite
7	600	30...31	Sorbite
8	650	28...29	Sorbite
9	700	24...25	Sorbitlike pearlite

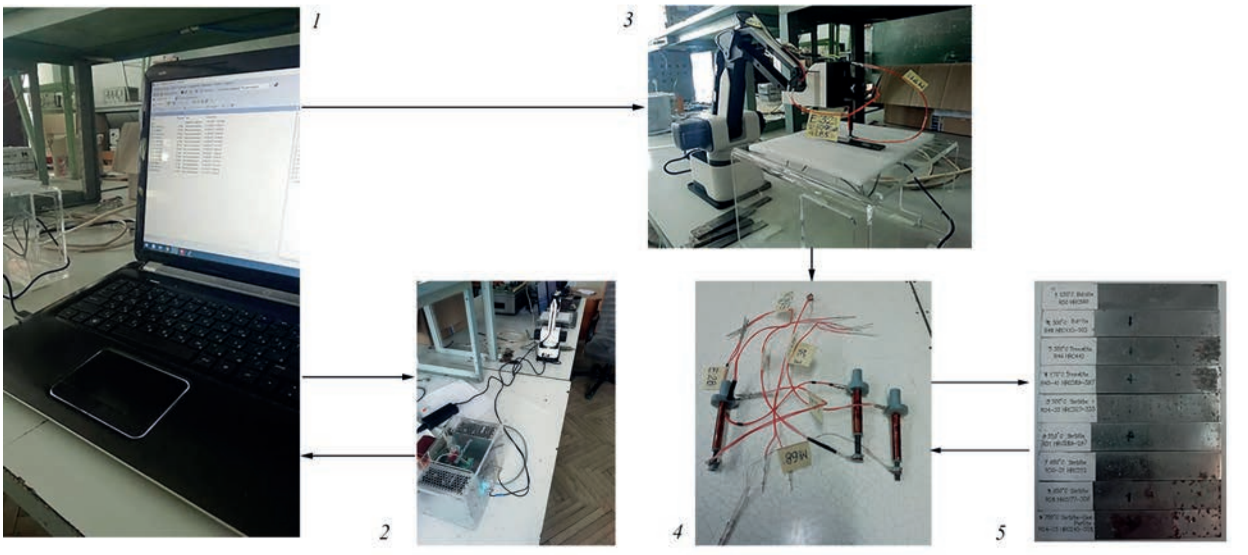

Fig. 3. System for automated analysis of measurements in alloy samples by the eddy current method: *1* – control unit (computer), *2* – unit for synthesis and processing of signals, *3* – robotic scanner, *4* – eddy current converters, *5* – samples under control
Рис. 3. Система для автоматизованого аналізу показників зразків сплавів вихрострумовим методом: *1* – блок управління (комп'ютер), *2* – блок синтезу та обробки сигналів, *3* – роботизований сканер, *4* – вихрострумові перетворювачі, *5* – об'єкти контролю

ject of control of the system is the process of synthesis of the excitation signal, the purpose of control is to change the ECC operation mode, that is a stepwise increase/decrease of the ECC electromagnetic field to a given value, to perform a set number of measurements, and also to change ECC coordinates in case of using a robotic scanner (*3*). The operator sets the initial operating conditions of the system such as frequency, initial amplitude and phase, the value of the amplitude change step, the number of steps to change the amplitude of the ECC excitation signal, and the number of measurements of the amplitude and phase of the polyharmonic ECC response signal. For the robotic scanner, the scanning coordinates and the trajectory for scanner to move according to these coordinates are set.

In our study, the system was programmed to perform 200 measurements with a change in the ECC operation mode, that is a stepwise increase in its electromagnetic field in the range of 255...1390 A/m at the frequency of the excitation signal with the completion of measurement when the control signal reaches 0.43 V. According to the measurement results, we obtained APAC of the response signal, which are functional dependencies $A_k = f(H_E)$, $\alpha_k = f(H_E)$, where A_k is the voltage amplitude of the k^{th} harmonic, α_k is the initial phase of the k^{th} harmonic, H_E is the intensity of the excitation electromagnetic field. Fig. 4 presents APAC for all samples of the 5^{th} harmonic, which is considered the most sensitive to the structure of carbon steels [27], dependence $A_5 = f(H_E)$ is marked with symbols A1-A8, vertical axis of values on the right, and the dependence $\alpha_5 = f(H_E)$ with symbols P1-P8, vertical axis of values on the left, respectively.

The samples on Fig. 4 are marked as St40X-N, where N is the number of the sample. Functional dependencies $A_5 = f(H_E)$ and

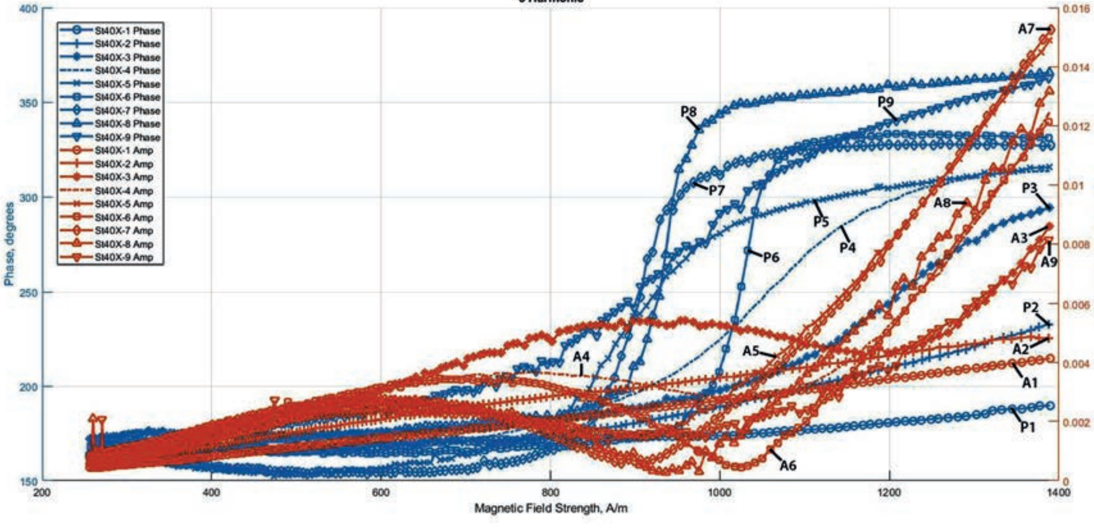

Fig. 4. APAC of the response signal of the 5^{th} harmonic for steel samples №№ 1–9
Рис. 4. АФАХ 5-ї гармоніки сигналу відгуку для зразків зі сталі №№ 1–9

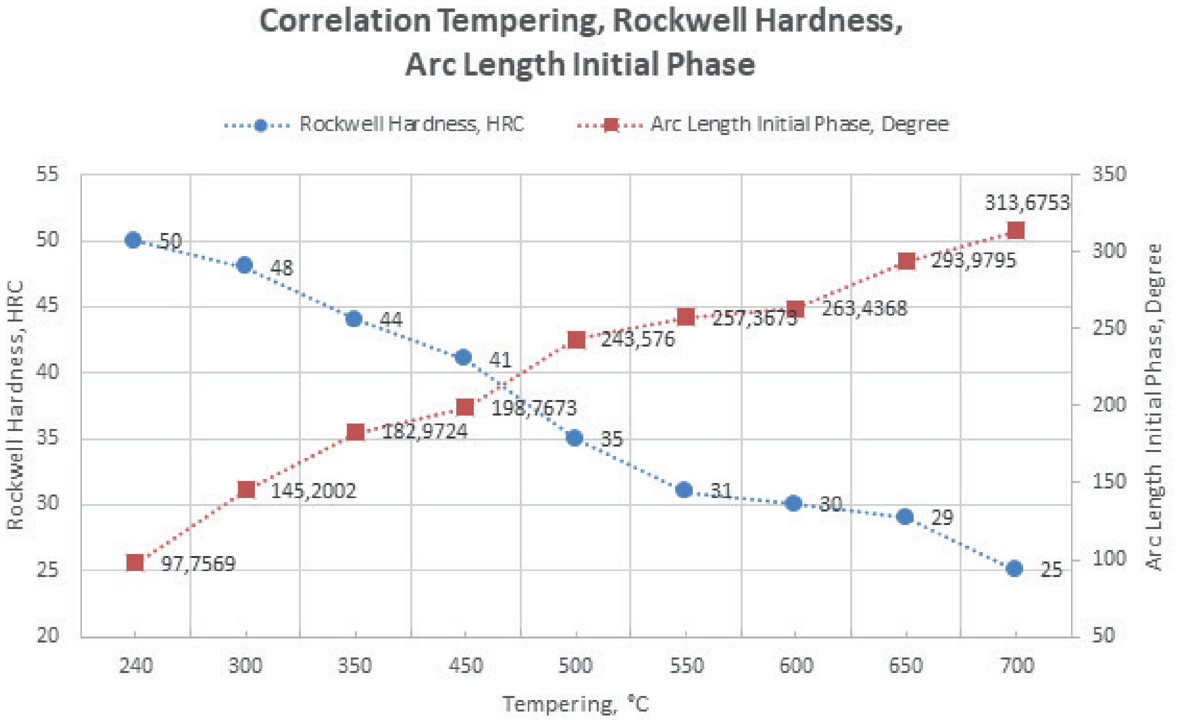

Fig. 5. Diagram of correspondence between the hardness of samples, types of microstructure and the curve length of the initial phase of the 5th harmonic and the tempering temperature of the samples

Рис. 5. Діаграма відповідності твердості зразків, типу мікроструктури і довжини кривої початкової фази 5-ї гармоніки температурі відпуску зразків

$\alpha_5 = f(H_E)$ have the domain of determination as $D_{H_E}(f):[256,1;1390,0]\frac{\text{A}}{\text{м}}$, and range $A_5 = f(H_E)$ as $E_{A_5}(f):[0,095;12,765]\,\text{мВ}$ and dependencies $\alpha_5 = f(H_E)$ $E_{\alpha_5}(f):[152,41;365,61]$ Degree.

As it can be seen from Fig. 4, the dependencies $A_5 = f(H_E)$ and $\alpha_5 = f(H_E)$ are non-linear, and they follow different paths. Taken the fact that the initial voltage phase of the harmonic, induced in the measuring coil of the ECC is sensitive to the microstructure of carbon alloys due to their magnetic properties [28], we have analyzed the dependence $\alpha_5 = f(H_E)$. For this purpose, the length of dependence curve $\alpha_5 = f(H_E)$ was calculated for each sample by summarizing straight line segments of the polygonal curve built up by points defined by vectors of excitation signal voltage values u_E and initial phase of the 5th harmonic response signal voltage α_5 according to the formula

$$L_{\alpha_5} = \sum_{i=2}^{n} \sqrt{(u_E(i) - u_E(i-1))^2 + (\alpha_5(i) - \alpha_5(i-1))^2},$$

where i is the index of the vector element (i = 2, 3, 4,… …n), n is the number of elements of the vector values.

Based on the results of calculations, a diagram of the relation between the hardness of samples and the length of the 5th harmonic initial phase curve and the tempering temperature of samples was built (Fig. 5), which also indicates types of microstructure and numbers of samples according to the table. On this diagram the horizontal axis is graduated in values of the tempering temperature of samples, the left vertical axis is graduated in the values of their hardness (points in the form of circles on the diagram), the right vertical axis is graduated in the values of the calculated length of the curve of the initial phase (points in the form of squares on the diagram). The diagram shows that the nature of the change in hardness values of the samples coincides with the nature of the change in the values of the initial phase curve length, given that as the tempering temperature increases, the hardness decreases and the length of the initial phase curve increases. This indicates the presence of signs of correspondence between dependence $\alpha_5 = f(H_E)$, which is part of the APAC of the ECC polyharmonic response signal, and the type of heat treatment, microstructure and hardness of the 40X steel sample.

Conclusions

Presented are the results of studying the heat treatment of nine samples from 40X steel by such traditional methods as measuring hardness and qualitative stereometric metallography, as well as by the proposed by us multifrequency eddy current NDT method which was implemented in the developed by us automated open-circuit system of program control over the APAC measurements of polyharmonic response signals. It is established that programming the parameters in the series of measurements according to certain algorithms results in the appearance of the correspondence between the tempering temperature values of heat treatment of the sample defined by the microstructure of the sample, its hardness and phase characteristics of the response signal of the 5th harmonic. This correspondence appears due to manifestation of the connection between the phase characteristics of the 5th harmonic response signal and the magnetic properties of the CO material as a result of the change in ECC operation mode, which is achieved by program control according to certain algorithms.

This indicates that the system developed by us can be used as an alternative to the traditional methods of testing and research in metallurgy, mechanical engineering, and operation of infrastructure at testing products from steel alloys with pronounced magnetic properties. The application of algorithms for automatic control of the mode of eddy current ECC allows optimization of measurement operations and searching for a more robust correlation of APAC polyharmonic response signals with physical, chemical, and mechanical properties of magnetic materials, which will be presented in our next publications.

The system developed by us is realized on digital components of synthesis and processing of signals that allows programming algorithms of ECC operation mode of any complexity which makes it easy to adapt to the conditions of solving various problems of quality control of products. The obtained values of amplitudes and initial phases of higher harmonics of the response signal under the condition of correlation with different material properties are «digital duplicates» of these properties and can be used as data in automated decision making systems, including self-regulating Industry 4.0 systems.

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Надійшла до редакції 20.12.2021