REVIEW SOME OF NON-DESTRUCTIVE METHODS FOR PHYSICAL AND MECHANICAL CHARACTERISTICS TESTING OF THE MATERIAL OF ROCKET BARRELS AND ARTILLERY SYSTEMS

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Abstract. Barrels of missile and artillery systems during intensive operation are exposed to high temperatures, alternating loads, and corrosive aggressive environments. These effects lead to rapid degradation of the metal, changes in its structure, the appearance of intergranular corrosion, microcracks, and changes in the physical and mechanical properties of the material as a whole. The combined effect of the above factors leads to the inability of the structure to withstand operating parameters and its rapid destruction. In structures such as barrels of missile and artillery systems, this process is extremely fast and difficult to predict in time. The article presents an analysis of the main methods of non-destructive testing of the physical and mechanical characteristics of steels, analyzes their advantages and disadvantages, and describes their areas of application. Studies of modern experience in measuring the physical and mechanical characteristics of metal structures show that there is a certain imperfection and limitation of the method of controlling the characteristics of a metal structure by separately taken informative parameters based on a separately selected method. More perspective and the one that is currently developing most intensively is a complex method to determining physical and mechanical characteristics.

Keywords: Measurements, non-destructive testing methods, physical and mechanical characteristics, technical condition, metal structures, diagnostic information, multi-parameter tasks.

1. Introduction

The basis of diagnosing metal structures, which also include the barrels of missile and artillery systems, is the principle of consistent and systematic measurements of certain physical parameters, detection of changes in these parameters during operation and comparison with the initial ones, and prediction of changes in these parameters [1].

The physical parameters themselves are divided into the following groups: kinematic, geometric, static, dynamic, thermal, acoustic, electrical and magnetic, mechanical, atomic-physical, as well as those based on the molecular properties of materials.

The basis of various methods and devices for the technical condition monitoring is the measurement of these physical parameters. The reliability parameters of metal structures are among the most important in the practice of technical diagnostics and they are functionally dependent on the measured values obtained during electrometry, vibroacoustic, flaw detection, structural analysis, measurement of mechanical properties, composition of matter, deformations, etc.

Devices that implement the diagnostic procedure can be conditionally divided into operational and diagnostic tools based on the method of their use. They are used in manufacturing, preventive inspections, repairs, technological tests, pre-commissioning tests, directly in the working conditions of metal structures, etc. and can be both hardware and software [2].

Assessment of the technical condition of metal structures and calculation of the residual resource involve maintaining a history of their operation, measuring and monitoring a sufficiently large number of diagnostic parameters, transmitting the obtained data, processing and interpreting them, making decisions about the further operation of the metal structure and are carried out using computational (allowing for existing models of fracture mechanics) and physical (measuring and evaluating certain material parameters, in particular physical and mechanical characteristics) ways.

The calculation (the first) approach is based on the principles of either linear fracture mechanics or methods of the limit transition of materials undergoing deformation into an unstable state. The method of linear fracture mechanics allows for determining the critical values of their sizes for various classical types of defects, that is, sizes that are unstable for the situation specified in the calculations and should lead to the destruction of the structure. The disadvantages of this method are: the lack of a clear theory of the transition from the configuration of a real crack detected in the material of a metal structure to that which is the basis for calculations of linear fracture mechanics; wide ranges of changes in physical constants included in the calculation formulas, which leads to significant errors in the calculations.

In practice, the application of this method requires a large amount of preliminary preparatory work and subsequent measurement testing. In this case, a sufficiently large number of parameters included in the calculation model are subject to measurement, and then the moment of the onset of destruction is calculated based on their values.

When using the second approach, the actual physical and mechanical characteristics of the metal structures material for long-term operation are determined on witness samples or on samples cut directly from the structure, which is usually economically impractical primarily due to the need for complete or partial destruction of the structure. It is possible to make samples from damaged metal structure elements, but this raises a number of questions, in particular, how much the degree of damage to the metal of the damaged area corresponds to the main volume of metal of the entire structure, since during the manufacture of the sample, damaged metal can be removed, which usually leads to ambiguous results.

There are approaches based on attempts to extrapolate the physical and mechanical characteristics of samples obtained during laboratory tests simulating operational tests, as well as samples cut from a destroyed structure, to real ones that are in operation [3]. However, it is difficult to obtain relevant correlations using these approaches.

2. Goal

Metal structures such as the barrels of missile and artillery systems are subjected to significant alternating loads, high temperatures, and corrosive environments during operation. This effect leads to metal degradation, changes in its structure, the appearance of intergranular corrosion, microcracks, and changes in the physical and mechanical properties of the material as a whole. The combined effect of the above factors directly affects the residual resource of the metal structure, since changes in physical and mechanical properties and the merging of microcracks into macrocracks lead to the inability of the structure to withstand operating parameters, which often leads to its destruction. In structures such as the barrels of missile and artillery systems, this process is extremely fast and difficult to predict in time. Therefore, the detection of changes in the physical and mechanical properties of the material and the presence of microcracks at an early stage is extremely relevant for reasons not only of operability, but also of operational safety.

The purpose of this work is to analyze the main methods of non-destructive testing, their advantages and disadvantages, areas of application, and justify the feasibility of using those that are most suitable for measuring the physical and mechanical characteristics of steels from which the barrels of artillery and missile systems are made.

3. Overview of methods

Currently, the most promising is the diagnosis of physical and mechanical characteristics of the material of a metal structure by non-destructive methods. The most common non-destructive testing methods used to control the physical and mechanical characteristics of metal structures during their operation, depending on the physical principles of operation, are presented in Fig. 1 [4].

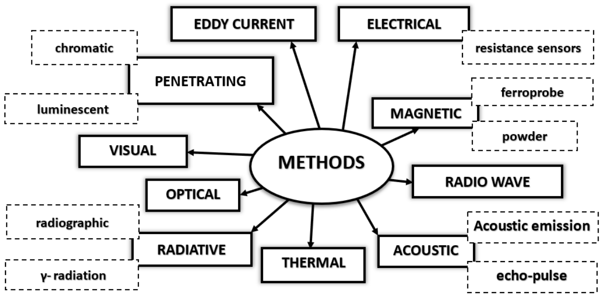

Fig. 1. Non-destructive testing methods of metal structures physical and mechanical characteristics

The name of each method includes a physical phenomenon, on the basis of which a specific control method is implemented. In particular, the acoustic method is based on the use of elastic vibrations that are excited or arise in the control object. The eddy current method is based on the analysis of the interaction of an external electromagnetic field with the electromagnetic field of eddy currents that are induced in the object by this field [5]. The radio wave method is based on the analysis of the interaction of electromagnetic radiation of the radio wave range with the control object. The essence of the radiation method is the analysis of ionizing radiation after interaction with the control object [6]. The electrical method is based on the registration of the parameters of the electric field that interacts with the control object or arises in the control object as a result of external influence. Thermal is based on the registration of temperature fields of the control object. Optical is based on the analysis of the interaction of optical radiation with the controlled object. The visual method is called organoleptic control, which is carried out by the human organs of vision [7]. The use of the magnetic method is based on the registration of magnetic scattering fields that arise above defects, or on determining the magnetic properties of the control object. Control by penetrating substances is based on the properties of substances to penetrate into the cavities of defects of the control object.

The listed methods, depending on the methods of their application, allow to obtain certain informative parameters, for example, the speed of radiation propagation, the magnitude of its attenuation, the specific electrical resistance, the coercive force, and others. They allow to estimate the target parameters of the technical condition of the metal structure, in particular the actual physical and mechanical characteristics, the presence (absence) or size of defects such as cracks, the residual thickness. One of the tasks of technical diagnostics, which can also be solved in this case, is the ability to move from the target parameters of the technical condition with sufficient accuracy and reliability to determining the degree of their change (degradation) in order to estimate the residual resource, assess risks, etc. However, each of the above methods has both its advantages and disadvantages. Let us briefly consider the main ones, which are most often used for non-destructive testing of the physical and mechanical characteristics of metal structures.

Currently, electromagnetic methods of non-destructive testing for assessing the actual state of the metal have gained significant development. Their specificity lies in the fact that the electrophysical properties of metals at the level of the crystal lattice are associated with mechanical properties, structural damage, chemical composition, heat treatment modes, elastic and plastic deformations. Therefore, electromagnetic methods allow to detect not only developed defects, but also stress concentration zones and structural elements in which irreversible changes have occurred at the level of the metal structure [8].

Determination of structurally sensitive electrical and magnetic characteristics of materials or products using an variable magnetic field is the basis of eddy current control of the structure and properties of materials. The possibility of such control is associated with the peculiarities of the behavior of metals in alternating fields, primarily with a change in its phase upon penetration into a conductive material and with the ambiguous dependence of magnetic permeability on the field strength.

For ferromagnetic materials and products, the magnitude of eddy currents depends on three parameters [9]: electrical conductivity, product dimensions and magnetic permeability. At the same time, magnetic permeability is also a function of the magnetizing field strength. The amplitude-phase method is based on measuring the amplitude and phase of the secondary electromotive force. When controlling ferromagnetic materials, there are increased requirements for the constancy of product dimensions and it is recommended to work at low frequencies of the electromagnetic field, when the influence of eddy currents can be neglected and it is assumed that the magnetic flux is distributed evenly over the product. In this case, the effective penetration depth of eddy currents is large and the field weakening will be insignificant. Higher harmonic components appear in the secondary electromotive force that arises when a ferromagnetic material is magnetized by a sinusoidal field [10]. Their use allows you to obtain additional information. (Fig. 2).

Magnetic methods of non-destructive testing are also widely used to measure the physical and mechanical characteristics of ferromagnetic materials. This method is not differentiated by the nature of the interaction of the physical field with the object of control. In all cases, the object is magnetized and the parameters used during control by magnetic methods are measured. Therefore, the magnetization operation for this type of control is mandatory. Depending on the specific tasks of non-destructive testing, the grade of the controlled material, certain primary informative parameters can be used [11]. The most common are the following informative parameters: coercive force, magnetization, induction (residual induction), magnetic permeability, tension, Barkhausen effect.

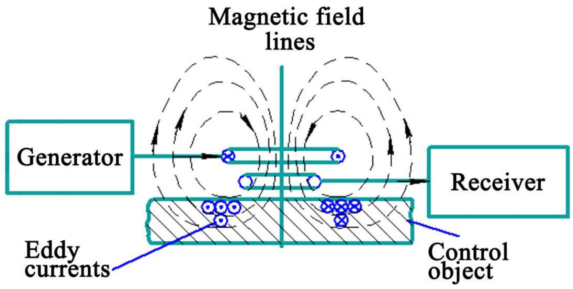

Fig. 2. Scheme of electrical conductivity control by eddy current method

Currently, indirect magnetic methods of controlling the stress-strain state of tubular metal structures are also widely used, which are based on the correlation of magnetic and mechanical parameters of the metal. Their advantage is non-destructive action, high productivity especially in field conditions, contactless control with the possibility of monitoring the stress-strain state of the metal structure during operation. The disadvantage is the significant influence of magnetic anisotropy on the final result.

The correlation between the magnetic and physical and mechanical characteristics of ferromagnetic materials occurs in cases where the physical and chemical processes of formation and restructuring of the structure and phase composition of the metal simultaneously form its magnetic properties [12].

The complex nature of the simultaneous influence of various factors on the magnetic and physical and mechanical properties of ferromagnetic materials often does not allow determining the influence of each factor separately. Therefore, in magnetic structureoscopy, the change in magnetic parameters is assessed and various physical and mechanical properties of objects corresponding to them are determined from them. When magnetically controlling the mechanical characteristics and structure of ferromagnetic materials, relative measurements are used, that is, they do not measure any magnetic or mechanical parameter, but only record whether the parameters of the control object correspond to the specified parameters or deviate from them. To assess how much the mechanical parameters of the part differ from the nominal ones, additional comparisons with the parameters of specially selected samples are required.

Another method, which can also be used to diagnose the condition of the barrels of missile and artillery systems, is based on the correlation dependencies between various mechanical and magnetic characteristics of ferromagnetic steels, while the magnetic characteristics were determined based on the analysis of the electromotive force from Barkhausen noise (Fig. 3). The effect of a stepwise change in magnetization is observed at an increased scale of the dependence of the magnetization of ferromagnetic materials [13]. The emergence of magnetic noise, or a stepwise change in magnetization, occurs both with changes in the intensity of the external magnetic field and with mechanical loads.

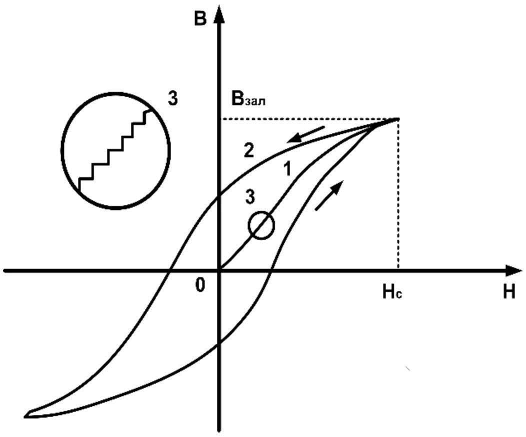

Fig. 3. Magnetization curves of ferromagnetic materials: 1 - main magnetization curve, 2 - hysteresis loop, 3 - jump-like character of magnetization, which is observed during precise measurement (Barkhausen effect)

When a ferromagnetic object is magnetized by an alternating magnetic field, the frequency spectrum of the induction has both discrete components that are multiples of the frequency and a continuous component called magnetic noise. Studies show that magneto-noise structureoscopy has good prospects due to the high sensitivity of the method and the ability to adjust to the influence of many interference factors. The parameters of the magnetic field can be set with sufficient accuracy using an electromagnet. In materials that have "positive magnetic anisotropy" (steels include these), the intensity of Barkhausen noise decreases when the metal is compressed, and increases when it is stretched. Based on the Barkhausen effect, a method for measuring mechanical stresses in tubular metal structures that operate under pressure is also currently being developed.

At present, a significant amount of experimental material has been accumulated on the correlation of magnetic properties of steels of various grades with their physicochemical and mechanical properties. The magnetic control method is used to determine: physical and conditional yield strength, relative elongation after rupture, relative narrowing of the cross-section after rupture, relative uniform elongation, plastic anisotropy coefficient, strain hardening and non-uniform plastic deformation indices, actual rupture resistance, hardness, grain size, sensitivity of steel to mechanical aging, impact bending, proportion of the viscous component in the fracture, bending angle or assessment of ultimate plasticity during bending, depth of the carbon-free layer, relative deformation, bending.

The use of acoustic means of controlling the physical and mechanical characteristics and structure of materials (grain size, elastic modulus, hardness, texture, strength, etc.) is based on the connection of these characteristics with the acoustic characteristics of materials (wave propagation velocity, elastic wave attenuation coefficient, characteristic impedance, etc.) [14].

Modern acoustic methods make it possible to study the state of the material by the speed and time of propagation of longitudinal, transverse and surface waves, by the measured values of the frequencies of natural oscillations of products, to conduct structural studies based on the data of the damping coefficient measurement [15], using acoustic spectroscopy methods, to evaluate mechanical properties based on the results of physical processes in the indenter, and to predict changes in the stress state of objects using acoustic emission methods.

Also, acoustic emission methods can be used to assess the level of damage. These methods have been developed to a sufficiently high level to date. The restructuring of the material structure, which is caused by the movement of dislocation groups, the emergence and development of cracks, and allotropic transformations in the crystal lattice, is accompanied by the appearance of elastic waves of the ultrasonic (less often sonic) range [16]. The acoustic emission method is based on the use of these waves.

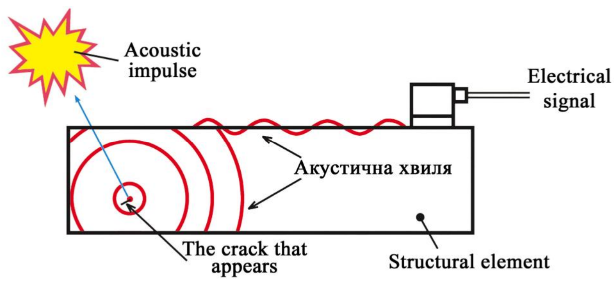

Fig. 4. Acoustic emission control scheme

Using such informative parameters as the number of signals per unit time, their frequency, amplitude distribution, location of the place of origin of elastic waves, they judge the state of the material, the changes occurring in it, and predict the operability of the structure.

The advantage of the acoustic emission method is the ability to detect microcracks at the stage of nucleation, but the difficulty of its application lies in the unambiguous selection of a useful signal that corresponds to the development of a defect, which under certain operating conditions develops with the greatest speed and can lead to the destruction of the structure.

Today, in the direction of improving acoustic control methods, a number of studies are being conducted aimed at separating from noise that arise due to the reflection of elastic waves from structural inhomogeneities, for example, crystal boundaries in a polycrystalline material [17].

Specific types of elastic waves in a solid are used: surface waves, waves in plates and rods. This significantly increases the limits of possible application of the method. The development of means for high-precision measurement of the propagation velocity of ultrasonic vibrations opens up the possibility of measuring internal stresses in solids by changing the velocity or attenuation.

Work is also underway to develop new methods for processing the information received, where computational ultrasonic holography is very promising. For example, using special piezo transducers, a large area (about 200x200 mm) of the surface of the control object is scanned. The information obtained is processed using specially developed software that uses the same algorithms that are implemented in optical holography when applying light radiation. This makes it possible to much more accurately present the shape and size of the detected defects and more reasonably judge their impact on the performance of the product. Thermoelectric control has found wide application due to the simplicity of design and operation of devices that implement this measurement method. The value of the thermo-electromotive force of a material when determining its belonging to a certain brand is significantly affected by such factors as the pressure and temperature stability of the hot electrode or the temperature difference between this electrode and the controlled object, the state of their surfaces, chemical composition, etc. The total thermo-electromotive force at the contact point is influenced by both the thermo-electromotive force of the formed film and its resistance to current flow.

The stability of thermo-electromotive force measurements in real production conditions is affected by a thin molecular layer of organic lubricant on the controlled surface with high resistivity, which can reduce the thermo-electromotive force value by 30-70%.

Another important factor affecting the efficiency of thermoelectric sorting by grade is the structural condition of the control objects [18]. The most stable results are obtained when sorting products that have undergone annealing, which ensures the absence of internal stresses, or normalization. This is also important for incoming control and sorting of metal blanks, from which, in particular, the barrels of missile and artillery systems are made. Incoming control and sorting can significantly reduce the number of defective products at the output, reduce production costs and improve product quality.

There is a fairly stable correlation between the structural state (phase composition, grain size, hardness), stresses in the metal and thermo-electromotive force. The thermoelectric method can detect zones of increased carbon, copper, silicon liquations, depending on the alloy composition and crystallization conditions.

The values of thermo-electromotive force and hardness directly depend on the carbon content in the solid solution. When the carbon content in the cemented layer is below the eutectoid, there is an unambiguous dependence of the thermo-electromotive force values on it, and at an equal or higher content, such a dependence is absent.

4. Method justification

Each of the mentioned control methods has its own advantages and disadvantages, application possibilities and limitations, speed and accuracy. Therefore, to develop a reliable and accurate system for monitoring the technical condition of the barrels of missile and artillery systems, it is necessary to develop a comprehensive method with a set of the optimal number of informative parameters, which would maximize the advantages and have a minimal impact on the final result of the disadvantages of each of the methods [18].

When choosing non-destructive testing methods, the following characteristics are important: sensitivity and discrimination; reliability of test results; reliability of equipment; simplicity of test technologies; test performance; safety requirements; requirements for the qualifications of specialists performing the test.

Also, the choice of the control method must be made taking into account the following factors: physical and mechanical characteristics of the product that can be measured; type of defect, its dimensions and location in the controlled product; operating conditions of the product and the requirements of the technical conditions or other regulatory document for the rejected product; material from which the product is made; condition and cleanliness of the surface treatment; shape and size of the product; availability of the product; control conditions.

The above, and the analysis of the works of other researchers on this issue, have shown the imperfection and limitations of the control of the physical and mechanical characteristics of metal structures by individual informative parameters based on a separately selected method. This is mainly due to certain features that must be taken into account, in particular:

- nonlinearity of the relationship between informative parameters and target characteristics, different accuracy of the values of informative parameters and target characteristics, which is critical for calculating and forecasting the residual resource;
- if we consider a set of informative parameters, we must take into account the fact that they may have mutual correlation;
- not the possibility of obtaining an analytical (in the form of a formula) relationship between informative parameters and target characteristics;
- for specific tasks of technical diagnostics, it is necessary to develop your own methodology for selecting a set of informative parameters.

The constant complication of modern technical systems, the growth of requirements for their reliability and the desire to avoid emergency situations lead to an increase in the number of structural parameters that are monitored and the improvement of the measuring instruments themselves [2].

5. Conclusions

Currently, the issue of a combined approach to determining physical and mechanical characteristics is being discussed more and more often in scientific circles. The difficulty lies mainly in the fact that for each group of steels it is necessary to choose its own unique set of methods and tools, which will provide a combined approach and allow to increase accuracy, speed and informativeness. However, some studies show that even within the same group of steels, a combined set of parameters that shows good results on one steel is not at all suitable for another steel.

Of particular interest are methods based on informative parameters that use various types of physical fields (magnetic, electric, thermal, acoustic, etc.).

Therefore, to develop a new method for multi-parameter control of the physical and mechanical characteristics of steels for missile and artillery barrel systems, further efforts should be directed to solving two main problems: choosing the optimal set of control parameters (the minimum number of parameters that will provide the maximum diagnostic information) and developing (or selecting from existing) appropriate measuring tools. At the same time, the implementation of this approach will require the use of modern methods for solving multi-parameter problems.

Conflict of Interest

The authors state that there are no financial or other potential conflicts regarding this work.

References

[1] Bolzon Gabriella. *Non-destructive mechanical testing of pipelines*. Lecture Notes in Civil Engineering. Book Chapter. 2021. ISBN 978-3-030-58072-8. DOI: 10.1007/978-3-030-58073-5_1.

[2] I.V. Rybitskyi, O.M. Karpash, V.Yu. Zapeka, P.M. Reiter, A.V. Yavorskyi, N.I. Chaban. "Substantiation of new diagnostic parameters of pipeline systems efficiency". The Paton Welding Journal, 2025, #4, 47-51 pages. https://doi.org/10.37434/tpwj2025.04.07.

[3] Yukhymets, P.S., Dmytrienko, R.I., Palienko, O.L., Yehorenko, V.M. "Mechanical properties of metal of critically thinned sections of the heat pipelines and features of their destruction". Tekh. Diahnost. ta Neruiniv. Kontrol, 4, 2022, 34-46 [in Ukrainian]. https://doi.org/10.37434/tdnk2022.04.06.

[4] EN 1330-2:2001. Non destructive testing - Terminology - Part 2: "Terms common to the non-destructive testing methods".

[5] EN 1330-5:2000 - Non-destructive testing - Terminology - Part 5: "Terms used in Eddy current testing".

[6] EN 1330-3:2000 - Non-destructive testing - Terminology - Part 3: "Terms used in industrial radiographic testing".

[7] EN 1330-10:2004 - Non-destructive testing - Terminology - Part 10: "Terms used in visual testing".

[8] Uchanin, V.M. "Surface EDDY current probes of double differential type as an effective tool to solve non-destructive inspection problems". The Paton Welding J., 2, 46-55. https://doi.org/10.37434/tpwj2023.02.07

[9] R.M. Solomakha, V.G. Rybachuk, V.M. Uchanin. "Distribution of effective coercive force of composite samples at its measurement by attachable magnetic transducers". Technical Diagnostics and Non-Destructive Testing. #3, 2023, pp. 3-9. https://doi.org/10.37434/tdnk2023.03.01.

[10] Zhou, L.; Wu, F.; Hall, R.; Davis, C. Electromagnetic sensors for in-situ dynamic microstructure monitoring of recovery and recrystallisation in interstitial free steels. J. Magn. Magn. Mater. 2022, 551, 169187. https://doi.org/10.1016/j.jmmm.2022.169187.

[11] HaSková, Lenka, USák, Elemír. "Non-destructive inspection of steel-based structural components: Exploring the potential of magnetic adaptive testing for measurement and Metrology". *AIP Conference Proceedings. Conference Paper*. 2024, pp.204-207.

[12] Elemír Ušák, Lenka Hašková, Daniel Vašut, Mariana Ušáková. "Modification of Magnetic Adaptive Testing: Progressive Method for Nondestructive Inspection of Microstructural Changes in Ferromagnetic Constructional Materials". September 2023Journal of Nondestructive Evaluation 42(3). DOI: 10.1007/s10921-023-00994-2.

[13] Ping Fu, Shurui Zhang, Yujue Wang, Xiucheng Liu, Hexuan Li, Peng Li, Cunfu He. "Theoretical model for the time-frequency spectrum of magnetic Barkhausen noise". NDT & E International Volume 158, March 2025. 10.1016/j.ndteint.2025.103553.

[14] EN 1330-4:2011 - Non-destructive testing - Terminology - Part 4: "Terms used in ultrasonic testing".

[15] S.Yu. Pliesnetsov, G.M. Suchkov, R.P. Mygushchenko, O.Yu. Kropachek, Yu.O. Pliesnetsov, A.V. Donchenko. Application of ultrasonic packet pulses of raleigh waves for testing the hardness of surface-hardened metals. echnical Diagnostics and Non-Destructive Testing) #2, 2023, pp. 28-33. https://doi.org/10.37434/tdnk2023.02.04.

[16] S.A. Nedoseka, A.Ya. Nedoseka, M.A. Yaremenko, M.A. Ovsienko, O.M. Hurianov. "Application of acoustic emission method to evaluate the changes in the properties of 17G1S steel after long-term service". Technical Diagnostics and Non-Destructive Testing. #3, 2023, pp. 26-30. https://doi.org/10.37434/tdnk2023.03.05.

[17] Yanming Guo, Donald R. Todd, David A. Koch, Julian D. Escobar Atehortua, Nicholas A. Conway, Morris S. Good, Mayur Pole, Kathy New, David M. Brown. "Grain Size Measurement of 316L Stainless Steel after Solid Phase Processing Using Ultrasonic Nondestructive Evaluation Method@. Volume 44, article number 124, (2025). 10.1007/s10921-025-01264-z.

[18] Mawhin M.A., Seuaciuc-Osorio T. "Nondestructive Microstructure Characterization of Tempered Martensitic Steels Through Data Fusion". Journal of Nondestructive Evaluation, Diagnostics and Prognostics of Engineering SystemsArticle2022. DOI: 10.1115/1.4054230.