Volodymyr Tonkonogyi[1], Maryna Holofieieva[2],
Oleksandr Levynskyi[3], Sergii Klimov[4], Predrag Dasic[5].

[1] Department of Information technology of engineering and design, Odesa Polytechnic National University, Shevchenko ave., 1, Odesa, Ukraine,e-mail: vmt47@ukr.net, ORCID: 0000-0003-1459-9870
[2] Department of Digital Technologies in Engineering, Odesa Polytechnic National University, Shevchenko ave., 1, Odesa, Ukraine, e-mail: mgolofeyeva@gmail.com, ORCID: 0000-0002-7632-9027
[3] Department of Digital Technologies in Engineering, Odesa Polytechnic National University, Shevchenko ave., 1, Odesa, Ukraine, e-mail: levinsky.o.s@op.edu.ua, ORCID: 0000-0001-9643-1494
[4] Department of Information technology of engineering and design, Odesa Polytechnic National University, Shevchenko ave., 1, Odesa, Ukraine, e-mail: 7873264@gmail.com, ORCID: 0000-0001-8174-6020
[5] Academy of Professional Studies Sumadija, 8, Kosovska str., 34000 Kragujevac, Serbia, ORCID: 0000-0002-9242-274X

THE DEPENDENCE OF THERMAL PROCESSES IN NON-METALLIC HETEROGENEOUS MATERIALS ON MECHANICAL VIBRATION LOADS

Received: February 15, 2023 / Accepted: June 1, 2023

https://doi.org/10.23939/ujmems2023.02.083

Abstract. One of the promising directions in the development of mechanical engineering is using of new non-metallic heterogeneous materials with high physical and mechanical properties. Such materials consist of two or more components (reinforcing filler and polymer matrix) and have specific physical and mechanical properties that are different from the properties of the constituent components. This is achieved by forming a complex developed structure. Reliable control methods play an important role in ensuring the quality of such structures. The paper considers an acoustic infrared thermometric method of control, which is based on the interaction of structural defects with acoustic waves. At the same time, thermal energy is generated at their boundaries, which is an indicator not only of the presence of cracks but also of their direction and development. a mathematical model has been developed that describes the transformation of the energy of mechanical vibrations into thermal energy, which occurs in non-metallic heterogeneous materials.

Keywords: non-metallic heterogeneous materials, acoustic infrared method of control, flaw detection, thermal energy, the energy of mechanical vibrations.

Introduction

One of the promising directions in the development of mechanical engineering is using of new non-metallic heterogeneous materials with high physical and mechanical properties. Such materials consist of two or more components (reinforcing filler and polymer matrix) and have specific physical and mechanical properties that are different from the properties of the constituent components. This is achieved by forming a complex developed structure. Such materials are characterized by high functionality and provide increased reliability, increased service life, reduced weight of products, and the ability to operate in extreme conditions [1]. The right choice of new materials for the relevant parts of the equipment, combined with technological processes aimed at obtaining the required accuracy and quality, can significantly improve the technical parameters of the equipment, its durability with a significant reduction in material consumption. The complexity of the structure of such materials implies the introduction of reasonable technologies for manufacturing products with integral elements of predicting their properties and diagnosing the state [2].

When designing materials with complex structures, the property of additivity does not always manifest itself [3]. This means that there is a change in the properties of individual components in the properties of their compounds through the organization of new structures [4]. That is, composites are materials consisting of at least two components with properties that their original components did not. A prerequisite is the presence of an interface between individual components (phases). It is possible to single out common signs of composite materials: heterogeneity and heterophase, multicomponent nature, the existence of interfaces between phases, as well as the difference in the physical and mechanical properties of the material from the properties of its components. Such features make it possible to attribute to heterogeneous materials any structures and media that have at least two phases interacting with each other through the interface and have properties that differ from the individual properties of the constituent components.

Thus, the whole variety of natural and artificially created materials can be represented in the form of heterogeneous structures and therefore can be described from a unified position of the theory of composite materials [4]. These materials have in common an interface between individual components, which should be represented as an area of change in material properties during the transition from one phase (structure) to another. Here, the interaction of components and phases occurs both during the manufacturing process and during operation, the redistribution of deformation and stresses under the action of operational and own loads.

Today, such materials are used for the manufacture of machine-building parts and allow for solving a wide range of technical and economic issues, including simplification of the technological process, reduction of the time of manufacturing parts, and the possibility of implementing new designs. They are used for the production of basic parts of machine tools (beds, crossbars, bases, frames, pedestals, columns), body parts (spindle headstocks, gearbox housings, tables, calipers), stamping equipment (punches, matrices for bending and drawing large-sized parts), holders cutting tool.

Problem Statement

Nonmetallic heterogeneous materials are very difficult objects to control. First of all, this is due to the anisotropy of properties, a large variety of types of structures. The complexity is also determined by such specific properties as non-magneticness, increased sound, and heat insulation. All this leads to the fact that the classical control methods for such materials are not effective enough and therefore require certain improvements [5]. The most effective methods of quality control of materials, which can be applied both at the manufacturing stage and during the operation of the product, are non-destructive methods. At the same time, they are indirect, that is, they do not allow one to directly count such parameters as structure, density, etc. This leads to the need for calibration using destructive and analytical methods. The latter, of course, requires a deep analysis of the ongoing internal processes in non-metallic heterogeneous materials that occur under external influences [6].

Review of Modern Information Sources on the Subject of the Paper

When analyzing the possibility of using one or another method for monitoring the parameters of products made of non-metallic heterogeneous materials, it is necessary to take into account the state of the material (it refers to dielectrics), structure, the ability to interact with the radiation used, dimensions and design features, the configuration of the control object, as well as the type of tasks being solved (diagnostics stiffness, density, measurement of dissipative properties, dynamic mechanical model of the material, flaw detection, etc.). One of the most promising control methods that can be used to diagnose the state of nonmetallic heterogeneous materials is the thermal method [7]. Here, the informative parameter is the temperature field of the surface of the object, which is a source of information about the features of the heat transfer process, which in turn depends on the presence and characteristics of internal and external defects [8]. In the presence of thermodynamic equilibrium of an object with the environment, an excess temperature field appears on its surface, the parameters of which are informative from the point of view of the object parameter of interest [9]. For example, quantitative and qualitative information about hidden defects can be obtained from the basic temperature function $T(x, y, z)$, which describes the change in the temperature field of the object surface at each moment of time.

The operation of thermal control methods is based on the interaction of the thermal energy of the control object with sensitive elements, such as a thermocouple, a resistance thermometer (means for measuring temperature by the contact method), a photodetector, a bolometric matrix, a liquid crystal indicator (a non-contact method for measuring temperature), converting thermal field parameters into an electrical signal and its transmission to the registration and indication device. Methods for measuring temperature using infrared technology devices have undoubted advantages due to their speed, the ability to detect radiation in the infrared and light ranges, high separating power, and, consequently, the detection of local and rapidly changing temperature differences on the surface of the test object [10]. Another advantage of the method under consideration is its non-contact, which excludes the removal of thermal energy from the object of control to the sensitive element of the measuring instrument, and therefore reduces the reverse effect of the measurement on the controlled processes to zero.

There are active and passive methods of thermal control. The latter does not require energy supply from an external source. Thermal fields in the object of control arise during its manufacture or operation. As for active thermal control, its implementation requires heating from an external energy source. There are various ways to implement such an impact (optical, microwave, convective). The using of vibrational perturbation of thermal energy is promising. Figure 1 shows a schematic diagram of the control of cracks in non-metallic heterogeneous objects by vibration infrared method.

Figure 2 and 3 shows the photo and thermogram obtained with the acoustic thermal imaging method for flaw detection of non-metallic heterogeneous materials using the carbon fiber plate as an example. According to the thermogram, it is clear that an elevated temperature is present in the defective areas. There is a delamination type defect in the upper left corner. In the center of the plate there is a defect obtained by the impact method. Around it there is an elevated temperature field, which, apparently, is caused by the presence of many microcracks

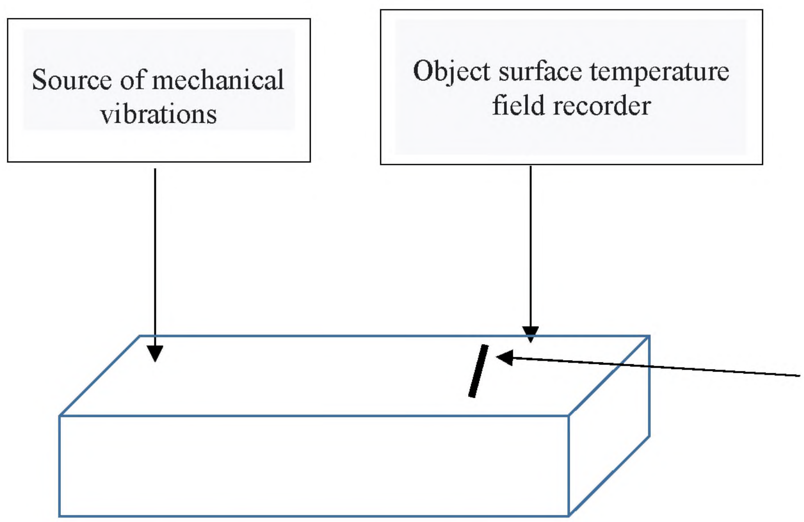

Fig. 1. Schematic diagram of the control of cracks in a non-metallic heterogeneous material by vibration infrared method

Fig. 2. The photo of a carbon fiber plate being tested

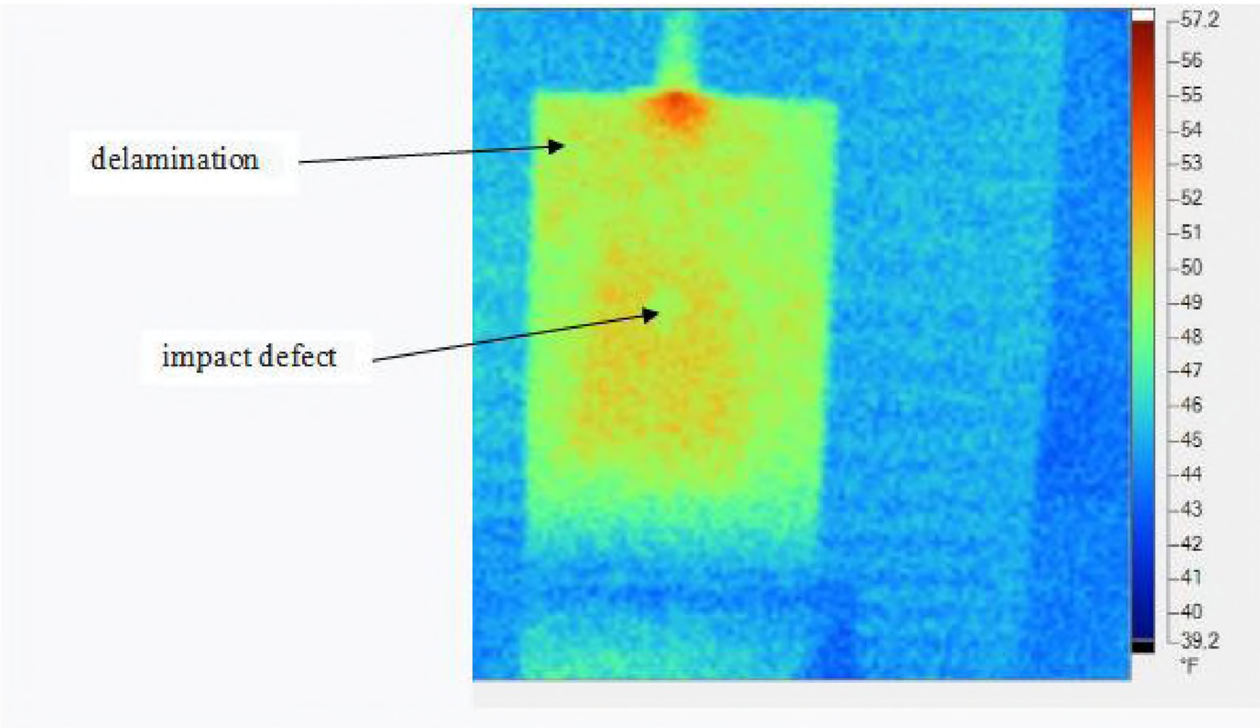

Fig. 3. Thermogram of the carbon fiber plate obtained
by acoustic thermal imaging method of flaw detection

Objectives and Problems of Research

The phenomenon of the occurrence of temperature fields in heterogeneous materials with structural defects under the influence of vibration is primarily due to the dissipation of the energy of mechanical vibrations on defects (especially on cracks). In addition, temperature gradients also arise during compression, tension, and fracture of materials [9]. This method of excitation of thermal energy compares favorably with the fact that it does not lead to heating in the defect-free zone. And, therefore, increases the signal-to-noise ratio. To implement the vibrational infrared method, it is necessary to use appropriate stimulation since it is based on a thermoelastic effect. The frequency of mechanical stimulation lies within the sound-to-ultrasonic range [11].

Features of internal processes occurring in nonmetallic heterogeneous materials under such an impact have not yet been studied in sufficient volume. Therefore, in order for the results of control of such complex objects with stochastic characteristics to be uniquely determined, it is necessary to study the parameters of the interaction of external influences with heterogeneous structures and describe them mathematically.

Main Material Presentation

The vibrational infrared method for monitoring heterogeneous structures is especially promising for objects operating under vibration conditions. If at any point in the medium in which closely located particles are under the influence of force, the process of mechanical oscillations is excited, then it will propagate from point to point with a finite speed. The latter is determined by the properties of the environment. The propagation of waves of any nature can be described using the same mathematical tools. The simplest type of oscillatory process is simple harmonic oscillation. At the same time, complex dynamic signals can be represented as a combination of simple harmonic components, each of which has its own frequency and amplitude and is connected in various proportions with other components. In this case, the system of functions has the form [12]:

$$f(t) = \frac{A_0}{2} + \sum_{i=1}^{\infty} \left(A_i \cos i\omega t \pm B_i \sin i\omega t \right), \quad (1)$$

where A_0, A_i, B_i – Fourier coefficients; i – an integer between 1 and ∞, called the harmonic order; ω – cyclic oscillation frequency; t – time;

Acoustic waves, passing through a non-metallic heterogeneous medium, interact with a large number of inhomogeneities that differ from each other. Of course, this affects the distribution of acoustic fields, since a change in such physical properties of the material as hardness, modulus of elasticity, density, structural uniformity, the presence of various defects leads to a change in the parameters of the acoustic wave itself (transit time, absorption, scattering, frequency spectrum). The considered materials are characterized by increased scattering and absorption in comparison with traditional materials [13]. Absorption is a direct conversion of sound energy into thermal energy, which is caused by a large number of processes. This is a kind of deceleration of particle oscillations. It should be noted that the absorption of vibrational energy in heterogeneous media usually increases in proportion to their frequency.

The most accessible acoustic parameter for measurement is the velocity of wave propagation in the medium under study. It is directly determined by the modulus of elasticity, Poisson's ratio, and the density of the material. Moreover, the speed of sound is also affected by the structure of the material and its stress-strain state [12]. The propagation velocity of a transverse acoustic wave in a non-metallic heterogeneous material, depending on its physical and mechanical properties, can be calculated as follows [14]:

$$c = \sqrt{\frac{E}{2\rho(1+v)}}, \quad (2)$$

where c – shear wave velocity; E – modulus of elasticity of the material; ρ – material density; ν – Poisson's ratio.

Let us consider the transformation of a sound wave as it passes through a non-metallic heterogeneous medium. Let the signal $u_1(t)$ be considered as the initial signal. Then $u_2(t)$ is the signal received after the wave passes through the material. Both signals were obtained using the same piezoelectric sensors under the same conditions. Then, taking into account (1), the mathematical model describing the transformation of an acoustic wave when it passes through the studied heterogeneous medium and taking into account the physical and mechanical characteristics of the material can be written in the following form:

$$u_2(t, E, \rho, \nu, \lambda) = K \cdot u(t) = u(t) \cdot \sum_{i=1}^{n} e^{-\lambda_i f_i S} \sin\left[2\pi f_i \left(t - S / c\right)\right], \quad (3)$$

where K is a coefficient that has the physical essence of the acoustic image of the material; S – sounding base (distance between sensors); f is the oscillation frequency; λ is the oscillation damping decrement.

Such a model considers that when vibrations are excited in nonmetallic heterogeneous materials, a number of vibration modes arise, and, therefore, the measuring signal is a combination of harmonic components that characterize the change in each vibration mode [15].

At the same time, the energy of a sound wave can be calculated by the following expression:

$$W = W_p + W_k = \int_V \frac{p^2}{2\rho_0 c^2} dV + \int_V \frac{\rho \vartheta^2}{2} dV, \tag{4}$$

where V is the volume; p – sound pressure; ϑ is the vibrational velocity of particles; ρ_0 is the density of the medium without sound; ρ is the local density of the medium.

Let us turn to the consideration of thermal processes that occur in non-metallic heterogeneous materials under vibration action on them. Anomalies of the thermal field on the thermogram may indicate the presence of artifacts in the volume of the material. The concept underlying thermal control is the temperature contrast or temperature gradient ΔT, which can be defined as the temperature difference in the investigated and defect-free zones. At the same time, it should be noted that the sign of ΔT depends on the ratio of the thermal conductivities of the base material and the artifact. If the latter has a higher thermal conductivity than the defect-free zone, then $\Delta T < 0$ [16].

In the absence of such defects as, for example, discontinuity, the generation of thermal energy is possible due to mechanical hysteresis during the cyclic loading of materials or due to plastic deformation during the initiation and propagation of cracks. The latter has a local character and explains the formation of plastic deformation zones due to the concentration of mechanical stresses at the boundaries of inhomogeneities of a heterogeneous structure. After the load is removed, if it does not exceed the elastic limit, the control object returns to its original temperatures and shape. For the studied materials, the dominant effect is the change in body temperature as a result of mechanical hysteresis, in which part of the elastic energy is irretrievably lost [17].

In [9], a mathematical model is presented that allows one to calculate the heating power in a crack perpendicular to the propagation vector of mechanical vibrations::

$$P = \frac{\mu \sigma_x S_{cr}}{T} \int_0^T \left| \frac{\partial x}{\partial t} \right| \partial t, \tag{5}$$

where μ is the friction coefficient of the crack wall; S_{cr} – crack area; σ_x – stress normal to the crack surface; x – displacement projection onto the x axis; T – temperature.

In addition to directly establishing the fact of the presence of a crack, thermographic analysis of the stress-strain state can be successfully used to study the processes of initiation and growth of cracks in heterogeneous materials under both static and dynamic loads [17]. It is known that in the heads of growing cracks, as well as in other zones of plastic deformation, anomalous thermal fields are formed, which not only indicate the presence of a crack but are also an indicator of their direction and growth. In accordance with the classical theory of Griffiths, destruction is understood as the process of energy unloading of the structure. In this case, the contribution of elastic energy to the energy of the system, depending on the length of the formed crack, can be described by the expression [17]:

$$\Delta W = -\frac{\pi \sigma^2 l^2}{E}, \tag{6}$$

where l – the characteristic size of the crack, equal to half the length of the crack L; σ – the stress applied at the crack boundary.

Then the crack length L is related to the released energy by the following dependence:

$$L = \frac{1}{\sigma_{av}} \sqrt{\frac{2E\Delta W}{H}}, \tag{7}$$

where σ_{av} – the critical stress causing crack growth; H – the depth of the crack.

In accordance with the law of conservation of energy, the total energy of an isolated system is constant. That is:

$$W_1 = W_2. \tag{8}$$

On the left side of the equation, we have the energy of the excited oscillations. The right side of the equation is the sum of the energy of mechanical vibrations, reduced due to dispersion, the energy released as a result of the formation of cracks, as well as the thermal energy generated in the anomalies of the material structure. Then, taking into account (3)–(6), expression (8) takes the form:

$$\left(\int_V \frac{p^2}{2\rho_0 c^2} dV + \int_V \frac{\rho \vartheta^2}{2} dV\right)\left(1 - \sum_{i=1}^{n} e^{-\lambda_i f_i S} \sin\left[2\pi f_i (t - S/c)\right]\right) = \frac{\pi \sigma^2 l^2}{E} + \frac{t \mu \sigma_x S_{mp}}{T} \int_0^T \left|\frac{\partial x}{\partial t}\right| \partial t. \tag{9}$$

Conclusions

Recently, the requirements for structural materials have increased significantly, as non-metallic heterogeneous structures are increasingly used. One of the advantages of the latter is the possibility of directed regulation of their properties and modes of using by selecting the composition, changing the ratio of components and macrostructure. At the same time, the problem of predicting quality and reliability plays an important role, in the solution of which effective methods and means of control are of particular importance.

It is promising to use an acoustic infrared thermometric method for quality control of non-metallic heterogeneous materials, which consists in generating thermal energy at structural defects by exposing them to mechanical vibrations. A mathematical model has been developed based on the law of conservation of energy, which characterizes the internal processes occurring in non-metallic heterogeneous materials when the energy of mechanical vibrations is converted into thermal energy.

References

[1] P. Melnichuk, V. Loev, V. Snitsar, S. Klimenko, "Modern materials at the workbench", *Bulletin of ZhDTU*, vol. 1, No. 52, pp. 38–50, 2010.

[2] Yu. G. Bezymyany, N. H. Brodnykovsky, E. A. Koziratskyi, O. V. Talko, "Acoustic non-destructive control of a multicomponent alloy based on niobium", *Bulletin of the National Technical University "KhPI". Series: Electric power engineering and converting technology. Coll. of science Working* , vol. 19, No. 1128, pp. 119–126, 2015.

[3] D. Roylance, "Introduction to composite materials". *Department of material science and engineering, Massachusetts Institute of Technology*, Cambridge, 2000.

[4] V. K. Mathur, "Composite materials from local resources", *Construction and Building Materials*, vol. 20, No. 7, pp. 470–477, 2006.

[5] M. A. Holofieieva, V. M. Tonkonogyi, M. E. Kolesnyk, "Control of the properties of materials with a multi-level structure", *East European Scientific Journal*, vol. 4, pp. 61–65, 2015.

[6] Yang Zhang, Yuqi Guo, Yan Chen, Luo Kang, Yabin Cao, Haibo Qi and Shaopu Yang, "Ultrasonic-Assisted Laser Metal Deposition of the Al 4047Alloy", *Metals*, vol. 9, No. 10, 1111, 2019.

[7] G. O. Oborskyi, O. S. Levynskyi, M. O. Holofieieva, "Doslidzhennya vplyvu vyprominyuval'noyi zdatnosti materialiv na tochnist' metodu teploviziynoho kontrolyu". ["Study of the influence of the emissivity of materials on the accuracy of the thermal imaging control method']. *Tekhnolohichnyy audyt i rezervy vyrobnytstva* [*Technological audit and production reserves*], vol. 2/3, No. 28, pp. 4–7, 2016 [in Ukrainian].

[8] Yin Li, Wei Zhang, Zheng-wei Yang, Jin-yu Zhang, Sheng-jie Tao, "Low-velocity impact damage characterization of carbon fiber reinforced polymer (CFRP) using infrared thermography", *Infrared Physics & Technology*, No. 76, pp. 91–102, 2016.

[9] J. Wang, S. Zheng, Visible and Infrared image fusion method based on wavelet transform and YUV, *Journal of Northwestern Poly Technical University*, vol. 3, No. 33, pp. 208–211, 2013.

[10] L. Furmankiewicz, M. Kozioł, R. Rybski, R. Szulim, "Concept and Implementation of Measurement Systems for Stationary and Remote Testing of Sensors for Electrical and Non-Electrical Quantities", *Sensors*, vol. 23, No. 4, 1928, 2023.

[11] V. Vavilov, D. Nesteruk, V. Khorev, "Ultrasonic and inductive IR Thermographic Procedures as Newly – Emerged Technigues in Thermal NDT", *Annual Journal of Electronics*, vol. 6, No. 2, pp. 102–109, 2012.

[12] P. Frankovský, D. Hroncová, D. Delyová, I. Virgala, "Modeling of dynamic systems in simulation enviroment matlab/simulink – SimMechanics", *American Journal of Mechanical Engineering*, No. 1, pp. 282–288, 2013.

[13] V. M. Tonkonogyi, M. O. Holofieieva, V. O Balan, "Doslidzhennya kharakterystyk rozsiyuvannya enerhiyi kolyvan'v bazovykh detalyakh verstativ z syntehranu" ["Study of the characteristics of vibration energy dissipation in the basic parts of syntegran machines"], *Cutting and instruments in technological systems: International scientific and technical journal*, vol. 85, pp. 282–287, 2015. [in Ukrainian]

[14] J. Krautkrämer, H. Krautkrämer. *Ultrasonic testing of materials*. Springer Science & Business Media, 2013.

[15] V. M. Tonkonogyi, M. A. Holofieieva, O. V. Nemchenko, A. A. Perpery, "Issledovaniye osobennostey formirovaniya akusticheskikh poley pri izmerenii dissipativnykh svoystv nemetallicheskikh geterogennykh materialov" ["Investigation of the formation of acoustic fields when measuring the dissipative properties of non-metallic heterogeneous materials"], *Bulletin of the Zhytomyr State Technological University. Series: Technical sciences*], vol. 2, No. 73, pp. 106–109, 2015 [in Russian].

[16] A. L. Gyekenyesi, "Thermoelastic Stress Analysis: An NDE Tool for Residual Stress Assessment of Metallic Alloys", *Journal of Engineering for Gas Turbines and Power*, vol. 124, No. 2, pp. 383–387, 2002.

[17] W. C. Zhu, C. A. Tang, "Numerical simulation of Brazilian disk rock failure under static and dynamic loading", *International Journal of Rock Mechanics and Mining Sciences*, vol. 43, No. 2, pp. 236–252, 2006.