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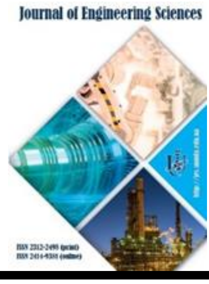

Prediction of Defects in the Structure of Non-Metallic Heterogeneous Materials

Tonkonogyi V.[1][0000-0003-1459-9870], Holofieieva M.[1*][0000-0002-7632-9027], Holofieiev Y.[1][0009-0002-1956-5338], Klimov S.[1][0000-0001-8174-6020], Naumenko Y.[1][0000-0002-6963-3995], Dašić P.[2][0000-0002-9242-274X]

[1] Odesa Polytechnic National University, 1, Shevchenka Ave., 65044 Odesa, Ukraine;
[2] Academy of Professional Studies Sumadija Department in Trstenik, 8, Kosovska St., 34000 Kragujevac, Serbia

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***Corresponding email:**
m.o.holofieieva@op.edu.ua

Abstract. Heterogeneous media can be represented as specially organized heterogeneous materials. The complex process of forming heterogeneous materials and media as systems is realized by gradually transitioning from one state to another. The presence of many one-time transformations of space-time structures causes the latter. When simulating damage such as cracks and fractures in products made of non-metallic heterogeneous materials, which consists of "assigning" the place of damage to the product at a specific moment in time, neither the method of random selection from the previously compiled list of "dangerous" places, nor the method of transfer to the object can be used, which is modeled, the results of field and operational tests of other products of a similar class or even other products of the same class. Therefore, it is proposed to use a combined method of obtaining a stream of quasi-random numbers, that is, a stream of random numbers that are "modulated" by information about defects in the structure of the material of the product, which was obtained because of field tests of the products or during their operation.

Keywords: heterogeneous system, flaw detection, control method, defects prediction.

1 Introduction

To ensure the anticipatory development of technology in various sectors of the economy, including medicine, the military-industrial complex, and construction, more intensive use of new construction materials is necessary, which can become the basis for the recovery and development of many industries. Various kinds of heterogeneous structures, including composite materials, which have specific physical and mechanical properties different from the total properties of their constituent components, are increasingly being used. Unfortunately, the characteristics of such materials have a stochastic nature. In addition, composites are quite complex objects for diagnosis, as they are characterized by anisotropy of properties, a wide variety of types of structures, and specific physical properties (electrical, thermal, sound insulating).

The properties of both individual elementary components and the material depend on the state, type, mechanical characteristics, adhesive and cohesive forces of connection between individual components, and the total volume and length of the internal surfaces of the phase interface. The accumulated experience of establishing cause-and-effect relationships between the structure of heterogeneous materials and their parameters and properties allows for predicting the necessary quality characteristics of products made from them. Simultaneously, it should be noted that the state of the structure is affected not only by the initial composition but also by the technological factors of construction manufacturing, for example, compaction, intensity of mixing, and repeated mechanical or temperature effects. Therefore, for directed structuring of heterogeneous materials, it is necessary to identify and implement potential opportunities in the established sequence "composition – technology – properties".

However, considering the structure's complexity, in manufacturing parts from them, various defects may occur, such as cracks, delamination, air pockets, and uneven distribution of components by volume of material. Disadvantages include the variability of physical and mechanical properties. The question of the quality and reliability of heterogeneous materials, products, and structures is one of the most urgent problems of modern scientific and technical development. Effective methods and means of control are essential in solving such a problem.

Heterogeneous media can be considered as specially organized heterogeneous materials. The interaction of individual components and structural elements ensures the fulfillment of the functional purpose of the structure [1]. This allows for presenting these media as complex systems that meet the general requirements [2]. They consist of subsystems characterized by certain integrity, and a relationship exists between individual elements and subsystems [3]. An isolated system is a subsystem of a more extensive system [4].

The formation of heterogeneous materials and environments as systems is a complex kinetic process, accompanied by a gradual transition from one state to another, resulting from multiple transformations of spatio-temporal structures. Such structures assume the presence of many interacting components of the object. The latter allows for distinguishing this object from several others and assigning it a certain level of properties. The choice of one or another object for analysis depends on the purpose of the research. Simultaneously, the first modeling stage can be considered the selection of structural parameters.

The heterogeneity of the structure, on the one hand, makes it possible to create materials with a wide range of properties; on the other hand, it makes it difficult to describe the processes that cause the manifestation of these properties. The properties are understood as a set of physical and technical characteristics that determine their consumer purpose, are the objective reality of a specific material, and are revealed through relationships and interaction. The qualitative level of properties and their quantitative characteristics are determined by particular analysis and research methods [5].

Since the properties are interpreted as a reflection of the object's objective reality, it is interesting to identify specific internal characteristics (structures) that provide the necessary properties. A structure is understood as a set of stable connections of an object that ensure its integrity and identity to itself [6].

The research aims to develop a forecasting method based on the model of the accumulation process of operational defects in the structure of heterogeneous mediums that occur in the "designated" places of damage to the product at a specific moment in time.

2 Literature Review

During the development of research methods for products from a significant class of materials, considerable attention should be paid to modeling and design methodology issues. This necessity also arises when adapting classical methods for measuring the characteristics of non-metallic heterogeneous materials since they do not always provide an opportunity to reliably solve the tasks in controlling such products.

The creation and research of models belong to the project process, which is understood as the study of any declared processes or systems of objects by creating and developing their models [7]. Simple and complex, heterogeneous and complex models are allowed.

When describing several subsystems at once, it is necessary to use complex models. Simultaneously, it is possible to single out homogeneous complex models that describe complex phenomena with boundary conditions. When the action of various phenomena determines the result, heterogeneous models are used, for which a systemic approach that considers the development of the system with the expansion of ideas about the nature of the phenomenon is essential [8]. Thus, to describe a heterogeneous object, it is necessary to develop its model, representing its reflection at a certain scale level with defined boundary conditions [9].

As a result of analyzing methods for calculating heterogeneous materials, it was impossible to determine one that would consider the complexity of the discrete structure of the material, as well as the reflection of the latter in general and local physical and mechanical characteristics [10].

Such structural inhomogeneity can be highlighted when moving from a material model as a continuous medium to a material model represented as a set of discrete structural inhomogeneities [11]. Such an approach makes it possible to investigate the mechanisms of formation of heterogeneous material structures at all scale levels and, accordingly, to control the levels of structural inhomogeneities through changes in physical and mechanical properties in the understanding of continuous mediums.

The authors propose to use the principles and methods of schematic representation of internal processes in non-metallic heterogeneous mediums during their control. This rejects new opportunities for developing new technical solutions in their non-destructive control, which will ensure an increase in the quality and reliability of products made from the specified class of materials. In the issue of establishing a complex of physical and mechanical properties of a heterogeneous material, not only the presence of cracks but also their type, orientation, and number are decisive [12]. The relay element is a non-linear element of the model, which differs from others in that the change in the characteristics of the internal processes occurring in the specified mediums is introduced in such an element once at each time interval, and the parameter value is maximum [13].

Building a schematic model of any process involves the following sequence of operations:

Firstly, an electrical model of a non-electrical process is created in the form of, for instance, an electrical circuit.

A complete mathematical analogy with electrical processes must be preserved here (capacitor – capacity, conductor – direction of transmission without losses, and resistor – transmission resistance).

Next, the model is optimized in its “electric form”. Simultaneously, the commonality between the transfer process of any component and the electrical circuit must be considered.

Finally, there is a return to the non-electric scheme, which is accepted as optimal.

This modeling approach significantly reduces the time required to represent the processes in the mediums under study.

To solve the problem of modeling defects in the structure of non-metallic heterogeneous materials such as a crack, particular additional elements can be used that simulate structural integrity violations relay elements. It is possible to single out the main requirements for the indicated circuit-technical elements [14].

First, it should be noted that only two states can describe such a relay element. When there is no defect in the object’s structure made of non-metallic heterogeneous material, the relay element is considered “off” and does not change the simulation result. The presence of a structural defect characterizes another case and, accordingly, the introduction of changes in the simulation result that consider the nature of the damage. The relay element is found in the “on” state.

The signal about switching of the relay element comes from the subsystem that models the mechanisms of transfer of an intensive parameter in a non-metallic heterogeneous material. An instance can be the internal processes that occur in such materials during their control by the acoustic, infrared thermometric method, which is based on the phenomenon of the release of thermal energy on the defects of the material structure under the action of the energy of mechanical vibrations, that is, the emergence of local zones of overheating of the object of control in the areas of structural homogeneity.

Another feature of such virtual circuit relay elements is its automatic switching at the end of each simulation iteration to calculate parameters of internal processes occurring in heterogeneous objects [15].

3 Research Methodology

The processes of synthesis and analysis, which are subject to both the structure of the principal scheme and the parameters of its elements, should be considered separately. Approaches to structure formation are determined by the stratification of internal processes occurring in the environment under investigation. To explain, for instance, we will consider the processes of defectoscopy using the acoustic, infrared thermometric method of a carbon plate with a pre-laid defect in the form of drilling. Simultaneously, the simulated processes were subject to two-level stratification and compliance with Table 1.

Table 1 – Stratification of objects of control with the acoustic infrared thermometric method of flaw detection

Level	Thermal processes	Mechanical processes
Micro	– release of thermal energy at defects in non-metallic heterogeneous materials; – transfer of thermal energy from one point of the research object to another due to thermal conductivity	– passage of mechanical vibrations of non-metallic heterogeneous material; – the emergence of a whole set of modes of oscillations, spreading in different ways and at different speeds; – energy dissipation due to internal damping in the viscous matrix and rigid filler; – structural damping of vibration energy at the matrix-filler interface, as well as on structural defects
Macro	– redistribution of thermal energy in the volume of the control object with anomalies in the locations of defects	– energy dissipation of mechanical vibrations
Meta	– obtaining information on the temperature distribution of the fields on the surface of the control object using infrared devices	–

Figure 1 shows a block diagram of the processes considered in Table 1.

Figure 2 shows a thermogram that demonstrates the processes described in Table 1.

The parameters of the simulated processes should be divided into two groups, considering the sources of information about their elements. The first group includes a priori parameters characterized by the physical and mechanical properties of elements at the micro level or the technical characteristics of the research object at the macro level. The second group consists of a posteriori parameter, the source of which is information obtained empirically, that is, because of experimental studies.

The most characteristic structural defects for products made of heterogeneous materials are cracks and delamination [16]. The place and time of appearance of such damages are, on the one hand, stochastic in nature, which is caused by the uncertainty of the conditions of the object’s manufacture and its operation. On the other hand, this process is entirely deterministic and is characterized by the distribution of internal mechanical stresses due to the design of the product [17].

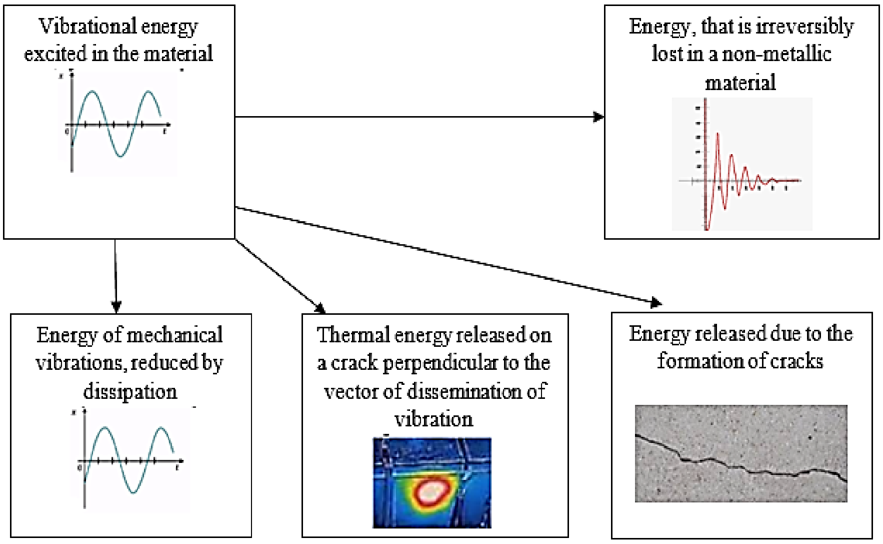

Figure 1 – The block diagram of the processes considered in Table 1

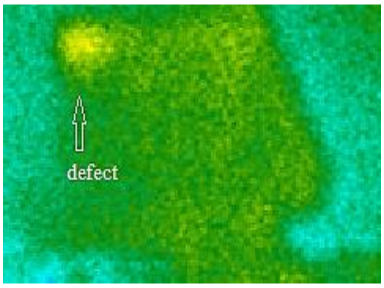

Figure 2 – The thermogram demonstrating the processes described in the Table 1

From this, it can be concluded that when forecasting the process of accumulation of operational defects in the structure of heterogeneous mediums on the model, which consists of "assigning" the place of damage to the product at a specific moment in time, neither the method of random selection from the previously compiled list of "dangerous" places can be used, nor the method of transferring to the modeled object the results of field and operational tests of other products of a similar class or even other products of the same class [18]. Therefore, the most effective can be considered the combined method of obtaining a stream of quasi-random numbers, that is, a stream of random numbers that are "modulated" by information about defects in the material structure, which was obtained because of polygon tests of products or during their operation [19]. Data on the stress-strain state of the product obtained on the model are also used [20].

The scheme of the organization of information flows within the proposed method is shown in Figure 3.

To carry out modeling, an array of information is formed regarding the parameters of the structure of the non-metallic heterogeneous material. The concept of "place of structure failure" is introduced for this. It clearly shows the location of the crack.

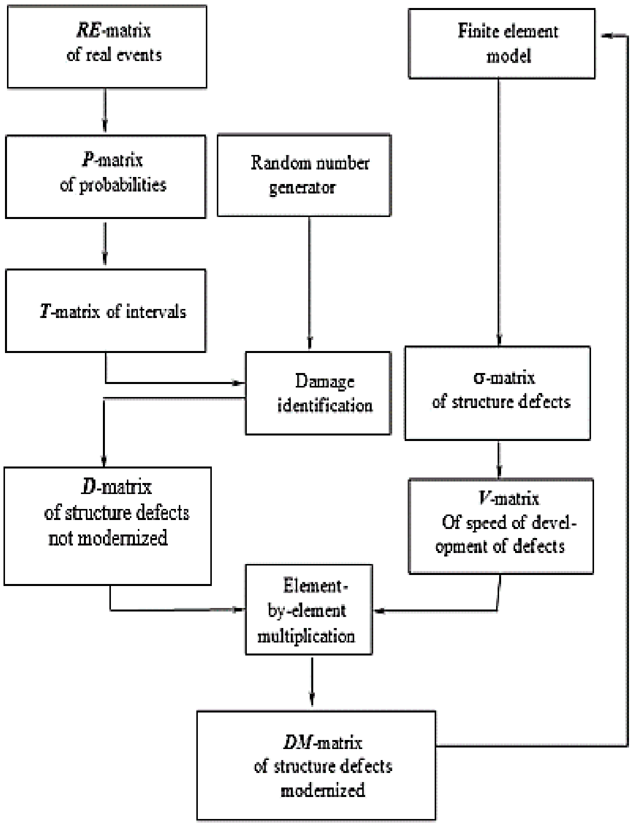

Figure 3 – Scheme of the organization of information flows

The total number of such places is entered into the D-matrix. If the specified model should consider the development of a "dangerous place" defect, then several relay elements are "inserted" into the cross-section of the product.

The results of the polygon studies lead to the RE-matrix of actual events, the size of which is $M \times N$, where N is the number of possible damage types to the structure, and M is the number of places of possible damage to a specific type.

Let us explain the physical and mathematical meaning of such matrices. All information regarding the model's location and number of virtual relay elements is represented by a two-dimensional array of numbers, the value of each element of which characterizes the number of relay elements and, accordingly, the length of the defect in the structure of the heterogeneous material under investigation. This array is the specified matrix. The matrix for the object, which does not foresee the appearance of defects, will be zero. Thanks to this approach, the final code of the relay element will have information about the defect type, location, and degree.

As indicated in [5], modernized *DM*-matrix A_δ^{Tt} can be obtained by element-by-element multiplication of each element of the non-modernized *D*-matrix $A_\delta^{T\delta t}$ by the corresponding elements of the so-called *V*-matrix of the speed of development of the defects A_V. Moreover, the elements can take both whole and fractional values. At iteration $(0 – T_0)$, i.e., when modeling the production of a product from a heterogeneous material, the elements of such a matrix can have a negative value since, at this stage, the technology can provide operations for "healing" the detected structural defects. If the development of a specific defect did not occur at this time iteration, the corresponding element will have the value "0". As a result, we get a V-matrix that considers the rate of development of a specific defect in a specific location of the structure of a heterogeneous object.

When the modeling of a heterogeneous object involves a change in energy flows in it, and such a change occurs due to a change in transfer characteristics, then, accordingly, the object model should contain elements that model the direction of transfer and elements that model its intensity. For this purpose, the v-matrix of the speed of development of defects is introduced into the scheme of the organization of information flows.

We denote by Z_{ijt} the number of structural defects of the *i*-th type in the *j*-th place, which occurred because of such tests at the time iteration $T_{t-1} – T_t$. Here, we will understand a step on the time scale and time iteration. It can be another resource parameter, for example, mileage. In this case, the probability of the occurrence of one or another structural defect at a specific time iteration, obtained experimentally, is calculated by the formula:

$$P_{ijt} = \frac{Z_{ijt}}{Z_\infty}. \tag{1}$$

For the development of a crack or delamination, which can be represented as a repeated occurrence of a structural defect, the probability can be increased by a pre-agreed value of K_{rep}:

$$P_{ijt}^{rep} = K_{rep} \cdot P_{ijt}. \tag{2}$$

We calculate by (1) the probability of all defects in the structure of products made of heterogeneous materials obtained during the same iteration. By selecting the maximum $M_{max}\{M_{max} \subset M\}$ among the elements of the array in each row and writing in each row on the right such number of zero elements that their total number becomes equal to M_{max}, we will obtain a rectangular matrix with dimensions $N \times M_{max}$.

After supplementing the incomplete rows with zeros, we obtain the *P*-matrix of the probability of the form:

$$\boldsymbol{A}_P^t = \begin{Vmatrix} P_{11} & P_{12} & P_{13} & 0 & 0 & 0 & 0 \\ P_{21} & P_{22} & P_{23} & P_{24} & P_{25} & 0 & 0 \\ P_{31} & P_{32} & P_{33} & P_{34} & P_{35} & P_{36} & P_{37} \\ P_{41} & 0 & 0 & 0 & 0 & 0 & 0 \\ P_{51} & P_{52} & P_{53} & P_{54} & 0 & 0 & 0 \end{Vmatrix}. \tag{3}$$

The matrix (3), like all the other matrices shown in Figure 1, has the dimension $N \times M$.

To build the *D*-matrix of defects in the structure of products made of heterogeneous materials, it is necessary to form the *I*-matrix, which will work compatible with the random number generator. The latter should be configured for iteration $T_{t-1} – T_t$ to work in the range $\{1 \ldots L{\cdot}Z_\infty\}$. Moreover, the more significant L, the more accurate the modulation.

In the unmodulated sequence of random numbers, all possible defects in the structure of the heterogeneous environment D_{ijt} are matched by equal magnitudes of the section of the segment of the axis $\{1 \ldots L{\cdot}Z_\infty\}$:

$$L \cdot \frac{L{\cdot}Z_\infty}{D_t}_{unmod}. \tag{4}$$

Each defective structure of the heterogeneous medium D_{ijt} must correspond to the whole number of elements of the segment of the natural number series. If the value of L_{unmod} because of calculations is a fraction, it should be rounded to the nearest whole number. Accordingly, we can only talk about the approximate equality of L_{unmod} segments for each D_{ijt}, and the accuracy of this approximation increases with the growth of L.

If we talk about the modulation of the flow of numbers in the range $\{1 \ldots L{\cdot}Z_\infty\}$, then it occurs by multiplying their number $L{\cdot}Z_\infty$ by weighting factors that are numerically equal to the probabilities P_{ijt} of the occurrence of the corresponding defects in the structure D_{ijt}:

$$L_{mod\,ijt} = L \cdot Z_\infty \cdot P_{ijt}. \tag{5}$$

4 Results

Displayed Figure 4 shows examples of non-modulated and modulated segments of several series. An unmodulated segment can be considered as modulating events of equal probability. As can be seen from the figure, the occurrence of, for example, the number 87 in the first case corresponds to the event "*A*", and in the second case to the event "*B*". Event "*C*" in the second case is not modulated at all, since the probability of its occurrence is zero, or was so small that when the corresponding L_{modijt} is rounded to the nearest whole number, we get zero.

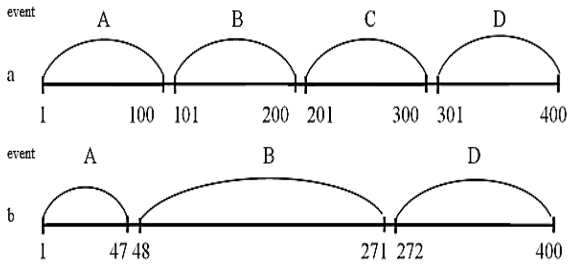

Figure 4 – Unmodulated (a) and modulated (b) segments of the natural series 1–400 by the probabilities of occurrence of 4 events

Information on intervals for each place of a possible defect in the structure of a product made of heterogeneous material is grouped into an *I*-matrix, which for a simple case (for example, shown in Figure 2) has the form:

$$\boldsymbol{A}_I = |47 \quad 271 \quad 400|.$$

The occurrence of numbers in the corresponding interval is recorded as a unit added to the corresponding element of the *D*-matrix. The algorithm of this procedure is as follows:

1) using the random number generator, Z_t of the first numbers from the stream of random numbers from the range $\{1 \ldots L \cdot Z_\infty\}$ is selected;

2) by processing the results of experiments and studies of a real object of the same class, modulated numerical intervals L_{modijt} are selected for all defects in the structure of products made of heterogeneous materials D_{ijt} and rounded to the nearest whole numbers;

3) the chosen numbers in the first point that fell into each interval according to the second point is calculated;

4) a matrix of size $M \times N$ with zero elements is formed.

5) the *D*-matrix is formed at iteration $(T_{t-1} - T_t)$. Simultaneously, to each of the zero elements combined in the matrix, many units are added according to the first point as included in the interval according to point 2.

At iteration $(0 - T_0)$, i.e., when modeling the production of a product from a heterogeneous material, the number of units added to the zero matrix is determined by the elements of the matrix of the probability of technological defects in the material structure.

5 Discussion

Heterogeneous materials and mediums can be represented as specially organized structures. Simultaneously, ensuring the fulfillment of the functional purpose of the product is performed through the interaction of individual constituents and structural components. This approach makes it possible to present heterogeneous materials and products from them as complex systems that meet general requirements. That is, they consist of subsystems characterized by a certain integrity. However, there is a close relationship between individual elements and subsystems.

It should be noted that the formation of heterogeneous materials as complex systems is a rather complicated kinetic process, during which there is a gradual transition from one state to another and, accordingly, multiple transformations of spatio-temporal structures. Simultaneously, the selection of structural parameters can already be considered the first modeling stage.

Issues of modeling and design methodology are of particular importance in the development of methods of research or flaw detection of non-metallic heterogeneous materials and products made from them. In addition, similar problems arise when adapting existing classical methods of measuring the parameters of material processes. This is caused by the fact that the mentioned methods do not allow reliably solving the questions in the case of counter products made of non-metallic heterogeneous materials due to their particular characteristics (non-magnetism, increased sound and vibration absorption, and low electrical conductivity).

Schematic design approaches make it possible to create a diagram of the future object, which, being manufactured, will be able to achieve the set goal. Such a scheme can be characterized as simple and clear. It is easily transformed into mathematical models, allowing one to consider many external and internal factors. Another advantage of schematic models is the possibility of simulating special properties and specific situations that may arise both during the manufacturing of products from non-metallic heterogeneous materials and during their operation.

6 Conclusions

In developing research methods for non-metallic heterogeneous materials and mediums, modeling and design methodology issues are of particular importance.

It is shown that when forecasting on the model of the process of accumulation of operational defects of the structure of heterogeneous environments, which consists in “assigning” the place of damage to the product at a specific moment in time, neither the method of random selection from the previously compiled list of “dangerous” places, nor the method of transfer to the simulated object, the results of field and operational tests of other products of a similar class or even other products of the same class.

The described approach allows for creating an unambiguous model of the object under investigation. Its main advantage stems from the fact that currently, special programs, including computer programs, allow for building such models based on the purpose of the designed object’s functioning and its creation capabilities.

The developed models make it possible to link such parameters as the distribution of temperature fields of a surface heterogeneous object during its control by the acoustic, infrared thermometric method with extensive parameters of the elements of this process, such as information about the presence of structural defects and their geometric characteristics, including the depth of occurrence.

In the future, it is planned to conduct studies to test the possibility of using the developed modeling method for a more comprehensive class of materials.

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