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QUALITY CONTROL METHODS AND MODELS OF POLYMER COMPOSITE MATERIALS

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Abstract. This article analyzes the traditional and modern methods of demolition control applied to structures made of polymer composite materials. Polymer composite materials are designed to ensure the strength of structures with a minimum mass, not subject to corrosion, etc. as there are advantages. But such materials require a special approach in the preparation and creation and the application of new methods, tools and solutions. This is due to the fact that there are many different types of polymer composite materials. Therefore, the development of criteria for the analysis of quality control methods and models, reliability forecasting in the technology of manufacturing products from polymer composite materials is an urgent issue. The authors give recommendations for the selection of methods for a complete assessment of the quality of compositional materials. The analysis of effective methods of quality control and forecasting of reliability of polymer composite materials was carried out. For this purpose, factors for the choice of the method and reliability prediction have been identified, taking into account its complexity for controlling polymer composite materials. Models for controlling polymer composite materials and products made on its basis were selected and on their basis the effectiveness of the application of low-frequency ultrasonic devices at the separation boundaries of controlled environments was determined.

Keywords: *Polymer composite materials, control methods, homogeneous isotropic medium, homogeneous transversal-isotropic medium, homogeneous orthotropic medium, combined double medium, triple medium, multilayer medium, control without dispersing.*

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1. Introduction

The application of polymer composite materials (PCM), which are widely used in modern technology and have a number of advantages over traditional materials and metals, in the defence industry and especially in the fields of aerospace engineering is a promising direction. Such materials ensure the strength of constructions with a minimum mass, do not suffer from corrosion, etc. However, the preparation and creation of such materials require a special approach and the application of new methods, tools and solutions. This is due to the fact that there are many different types of polymer composite materials. So, they depend on the specific features of their structures, production

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technology, physical-mechanical and strength characteristics, variety of types of defects that appear during the production and operation process, etc. they differ from each other due to reasons (Gojayev *et al*., 2020a; 2020b; Rotkovich *et al*., 2023; Vera-Serna *et al*., 2023; Hajiyeva *et al*., 2022). Assessment of the stability of the technology of manufacturing products from polymer composite materials and analysis of quality control methods and models, reliability prediction and development of criteria is an urgent issue. As the fields of application of composite materials expand, there is a need to purchase new materials and study their physical and chemical properties. Therefore, recently extensive studies are being conducted in the direction of purchasing and researching new polymer-based composites (Arzumanova, 2021; Hsissou *et al*., 2021; Gojayev *et al*., 2019a; 2019b; Rahman *et al*., 2011).

The choice of this and other methods of quality control and the prediction of reliability are determined by the following factors: 1) by the aggregate state of the medium we control (gaseous, liquid, solid), 2) by the physical state of the controlled medium (dielectric, semi-conductor, conductor, magnetic, non-magnetic), 3) by the structure of the controlled environment (amorphous, monocrystalline, heterogeneous with iris structure, weak or strong anisotropic, etc.), 4) by the ability to interact with radiation (weak or strong absorption or weak scattering etc.), 5) by the control method (in vacuum, liquid, high temperature, under great pressure, etc.), 6) by the dimensions, configuration and structural features of the control object (small, medium, large-sized, simple or complex shape, single or multi-layered, glued, etc.); 7) by the type of problem to be solved (detectoscopy, thickness measurement, moisture measurement, density measurement, viscometry, control of hardening kinetics, control of stress-deformation state, control of the composition of components, etc.) (Budadin *et al*., 2007).

Polymer composite materials are a very complex object of control, because of the significant homogeneity of the structure, the anisotropy of the properties, the large variety of structural types (unidirectional, longitudinal-transverse, combined, etc.) and the specific physical properties: high electrical, thermal, sound-insulating properties is characterized by a large dispersion of physical and mechanical properties and small density values (0.02-2.0 g/cm^3). Most types of PKM refer to dielectrics or poor conductors depending on the type of filler we use. Practically all PKMs are non-magnetic materials. Therefore, in defectoscopy of metal products, for example, magnetic and eddy current control methods are in most cases unacceptable for defectoscopy of PCM. However, these methods can be applied to measure the thickness of PCM products. High-frequency ultrasonic methods are also not effective for PKM control, because ultrasonic waves with frequencies above 1MHz either cannot be transmitted to the controlled medium due to their strong absorption and scattering and significant surface roughness or they greatly exceed the range of controlled thicknesses. Radiation methods for PCM are more effective for defectoscopy and relatively for control of density and thickness because the sensitivity of defectoscopy with these methods with different values of radiation is three to four times lower than the sensitivity of defectoscopy of steel. It should be noted that PKM for this control method are available in both solid and semi-finished, liquid and connecting states (Mamedov & Mehdiev, 2019).

2. Research methodology

As a result of the analysis and evaluation of the effectiveness of the existing methods of non-destructive control for PCM, it was determined that the following methods are the most effective in non-destructive control of PCM: 1) low-frequency ultrasonic pulse; 2) radio wave; 3) infrared optics; 4) thermometric; 5) electricity. The main criteria determining the choice of given control methods are the following: safety for service to staff; sensitivity of control; accuracy and feasibility of control methods; the possibility of control mechanization and automation; ensuring high productivity of control; relative simplicity of control methodology; information capability and universality of control; availability and use of serial equipment; relatively small cost of control; the possibility of using service personnel without high qualifications. The indicated control methods can be used both individually and in combination. It should be noted that increasing the number of used methods leads to an increase in the value of control and a decrease in productivity along with increasing the sensitivity and information capacity of control. Therefore, complex low-frequency ultrasound and electrical methods can be the most effective. With the increase in quality control requirements, the number of methods in the complex can increase. In this case, the combination of low-frequency ultrasound, radio wave and thermometric methods may be more optimal (Rumyantsev & Dobromyslov, 2012). The selected methods allow determining a large number of different physical characteristics directly in the product: the speed and attenuation of elastic waves (longitudinal, sliding, bending, surface), transmission, reflection and refraction coefficients of these elastic waves; angle of rotation of the plane of polarization of sliding waves; electrical conductivity; tangent of the angle of dielectric penetration and electrical losses; transmission, reflection and refraction coefficients of electromagnetic waves.

3. Discussion of results

These electromagnetic waves can be in the infrared extremely high-frequency range. At the same time, other physical characteristics including heat and temperature transfer coefficients, etc. can be attributed. These characteristics determined directly in the product include the strength and hardness of the product, strength and elastic properties of the material, density, structure, composition of components, viscosity, degree of hardening, geometric dimensions, moisture, stress deformation state, etc. can be used for direct and indirect evaluation of such parameters.

Thus, the completeness of control is that, first, the optimal complex of physical parameters is determined, according to which the strength and other physical-mechanical characteristics of PCM and products based on them are determined; secondly, optimal methods and means of control of structural defects are developed and implemented and thirdly, an integral value of the product's performance is given according to the set of parameters determined by non-destructive methods. Determining the characteristics of PCM in the product recycling process makes it possible to eliminate the reasons that call for the destruction of the structure of the material in the product, the appearance of defects and the change of properties.

The systematization of the main models of controlled environments reflecting the cross-sectional structure of products from PCM is of interest due to the high diversity of different types of constructions and products from this material. In particular, this applies to large-scale constructions, which consist of isotropic, transversal-isotropic and orthotropic PCM from both single-layer and multi-layer elements. In addition, the combination of polymer and metal materials, composites and lightweight foam materials is common. Also, there is considerable interest in the provision of non-destructive control of the products during the preparation stage, their wrapping or thermal processing. For these elements, the double structure of the transverse section is the most characteristic: the upper layer is the material of the product (semi-finished product) and the lower layer is the material of the shower.

Based on the selected models, the development of the theoretical basis of the distribution and reflection of low-frequency ultrasound at the separation boundaries of the controlled environments is related to the necessity of determining the physical-mechanical, technological structural parameters of the composite materials in the controlled environment.

In the process of distribution and reflection of elastic waves in single-layer and multi-layer media, which differ in speed, significant anisotropy, ultrasound attenuation and structural inhomogeneity, there is a complex interaction of directly reflected and refracted waves, which creates great theoretical difficulties in solving this problem (Kapadia, 2006; Adams *et al*., 2002).

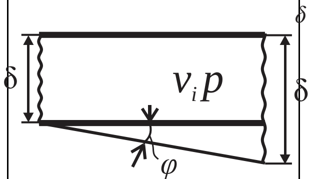
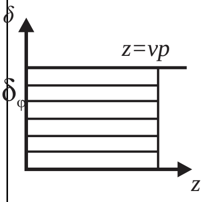
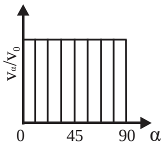
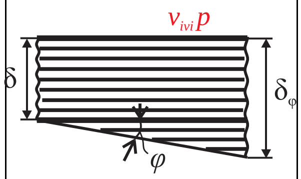
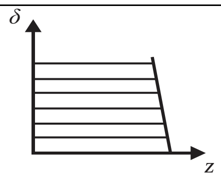
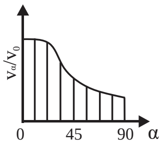
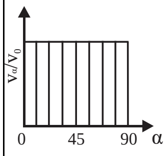
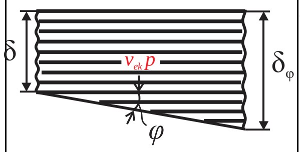
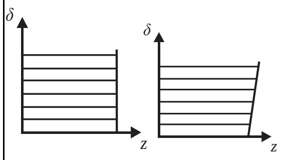
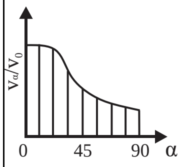
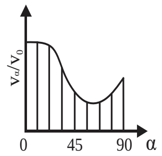
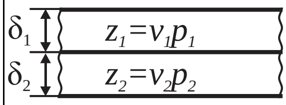
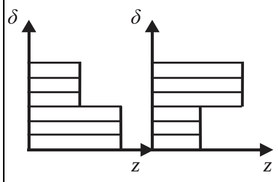
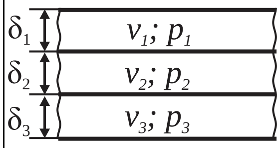
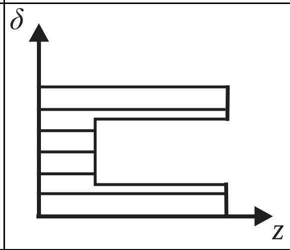
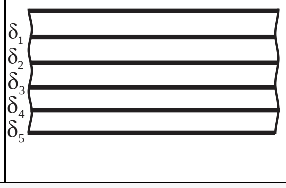
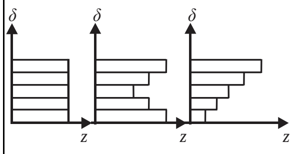
The main problem of both the high-frequency echo-pulse method and the low-frequency method is the maximum shortening of the length of the elastic pulse we are studying. At high ultrasonic oscillations, this problem has been solved by mechanical or electrical damping. Due to their high suitability for low-frequency converters, mechanical and electrical damping is not considered effective, because it leads to a significant increase in geometric dimensions and a decrease in the sensitivity of the converters. Therefore, to solve this problem, it is necessary to look at the whole oscillating process of piezo elements of different shapes and sizes.

For high-frequency transducers, this problem is solved by providing a large ratio between the diameter of the transducer and the wavelength of the induced oscillations. The transfer of this rule to low-frequency converters leads to a significant increase in the size of the converters, which makes them impractical for control (Vavilov *et al*., 2011; Larin, 2013; Babushkin *et al*., 2013).

For the analysis of the distribution of elastic waves in PCM products, it is necessary to choose the appropriate models of the environment that most fully reflect the cross-sectional structure of the structure or product. Depending on the configuration and geometric dimensions of the product, the control conditions will depend on the ratio of the wavelength and the dimensions of the product, as well as the shape reflecting the separation boundaries of the media. The most common types of models of controlled environments are listed in Table 1.

1. Homogeneous isotropic medium. This model fully reflects the structure of products made of unfilled polymer materials (fibreglass, polystyrene, block polyethene, kapron, etc.) or materials filled with small dispersed filler (glass fibres, carbonite, etc.). In some cases, for products with different thicknesses, there may be a violation of parallelism between the reflective and radiating surface and the media. In this case, it is considered that the field of application of the low-frequency echo-impulse method is limited to the medium, its thickness should not be less than one wavelength λ and the radius of curvature should be $R \geq 5\lambda$ at the borders of parallel separation. These conditions are necessary to ensure the opening of the products we receive in experimental studies.

Table 1. The most common types of models of controlled environments

Model	Sketch	The dependence of the product of acoustic resistance-z on its thickness (depth) - *δ*	Velocity anisotropy	
			in depth	in the plane
Homogeneous isotropic environment				——
Homogeneous transverse-isotropic environment				
Homogeneous orthotropic environment				
Combined duplex environment			——	——
Triplex environment			——	——
Multiplex environment			——	——

Note: The following abbreviations are accepted in the table: δ, δ_φ – product thickness; δ_1, δ_2, δ_3 ... δ_n – layer thickness of the environment; v, v_i – ultrasound velocity; α – the angle between the direction of the tests and the axis of elastic symmetry; v_α/v_0 – indicator of the anisotropy of ultrasound velocity; φ – the angle creating non-parallelism of the product's surface.

2. Homogeneous transversally-isotropic medium. The conditions of distribution of elastic waves in this environment are characterized by the fact that their speed of

distribution in the plane of the medium is constant and does not depend on the direction of distribution. The velocity in the transverse direction (from the plane) of the waves is a dependent parameter (it depends on the angle between the direction of distribution and the separation surface of the medium) and the velocity in the perpendicular direction (through the thickness) is constant.

The model of such an environment can be used to control products of various shapes and sizes made of PCM based on connecting and chopped fibre, reinforcing layers and other fillers. The most widely exhibited blocks, disks, prisms, rings and hollow-shaped rotary objects were obtained from these materials. The optimal conditions for the control of similar products are as follows:

$$\delta \geq \lambda; \quad R \geq 5\lambda; \quad a \geq 2\lambda \tag{1}$$

Here; δ, R, a – are the thickness of the product, the bending radius and the distance to the edge of the product, respectively.

The extreme values of the propagation speed of longitudinal waves will occur for directions parallel (maximum) and perpendicular (minimum) to the material's index. All other directions will have an intermediate value of longitudinal wave propagation. Some types of materials may have varying thicknesses dictated by the constructive characteristics of the material.

3. Orthotropic Environment. Among anisotropic polymer composite materials, the widest variability is exhibited by materials possessing an orthotropic environment. It is aligned with the three mutually perpendicular axes of elastic symmetry of the material. For such an environment (for each structural direction), the propagation speed of elastic waves can have different values. Considering that controlled environments are composed of a minimum of two different types of materials, either in the form of fine dispersion or fibrous fillers, their dimensions are significantly smaller than the wavelength of the wave, it is assumed that such a composite environment is both orthotropic and anisotropic. In this case, the degree of anisotropy is determined by elastic waves in directions perpendicular to the axes of elastic symmetry. For such an environment, the values of the speeds of elastic waves not aligned with the directions of elastic symmetry are a function of the direction of propagation and the angle between the propagation direction and the axis of elastic symmetry.

The formation of an orthotropic environment is made possible by encapsulating or wrapping layers of contact adhesive material with a contact adhesive bonding material. The orthotropic environment's uniqueness concerning elastic waves is due to the fact that the thickness of the elementary layers composing the orthotropic environment is significantly smaller than the wavelength of elastic waves. The key characteristic of an orthotropic environment is that the extreme values of the propagation speed of elastic waves occur in three mutually perpendicular directions: along the longitudinal, transverse, and normal directions to the material's index. In addition, the speed can have a minimal value in a certain direction, where it is perpendicular to the material's index. The state of this direction is determined by the degree of anisotropy of the environment, i.e., the speed in mutually perpendicular directions. Orthotropic materials have found the widest application in the manufacturing practice of large-scale structures. With a wide range of diameters, thicknesses and lengths, these materials are used to produce cylindrical, conical and spherical shell structures and they find applications in various industrial fields. It should be noted that this demonstrated model can primarily be applied to ready-made products, provided that it has been removed from the mould after curing (Maldague, 2001; Tong *et al*., 2002; Fawcett & Oakes, 2006).

4. Combined Bilayer Environment. The model of this environment allows for addressing questions related to the propagation of elastic waves, both in the manufacturing process of materials and in quality control issues in finished products. The preparation of large-scale materials is typically associated with the stretching of a composite material related to the configuration of the material being repeated. For laminar structures, they initially connect the part with adhesive, which has the same shape as the product, to the adhesive bonding material, usually in the form of a sheet, strip or rod. In terms of their overall structure, this environment is in line with the model we are considering, i.e., it is bilayered, with the lower layer being the adhesive material of the product and the upper layer being the material of the product (semi-finished product). In such an environment, the determination of the parameters of elastic wave propagation allows addressing issues in the stretching process (in the semi-finished product), in thermal treatment (in curing) and in the final product's technological parameters, for quality and quantity evaluation. Managing the technological process to obtain flawless products is made possible.

In many cases, the combined bilayer model can describe the structure of finished products, where it is necessary to protect the main material of the product from the harmful effects of temperature, humidity, sounds and chemicals. In this case, composite materials can perform both protective functions (thermal insulation covers, sound-insulating materials, chemical protection coatings, etc.) and the main material's function.

The application of bilayer environments in various combinations leads to a significant variety of options, among which the most typical are: 1) isotropic layer with an isotropic layer; 2) transversely isotropic layer with an isotropic layer; 3) orthotropic layer with an isotropic layer; 4) orthotropic layer with a transversely isotropic layer; 5) orthotropic layer with an orthotropic layer.

It should be noted that in combinations 4 and 5, solving the problem of elastic wave propagation is associated with the excessive complexity of mathematical apparatus. Therefore, simplified methods are possible in these cases. It should also be noted that poor preparation of materials and the disruption of adhesion between one layer and another can lead to the formation of an air layer (defect) between these layers (Berg & Adams, 1989; Stoessel *et al*., 2012).

5. Bilayer Environment. This model has found its most significant application in triple-layer constructions, where the first and third layers are made strong materials, while the inner layer is made of a lightweight and porous filler material (such as foam plastic, etc.). In this case, the thickness of the outer layers is considerably smaller than the inner layer. The acoustic resistance of the outer layers is relatively more important than the inner layer. In terms of the length of elastic waves, the outer layers are quite thin.

In lightweight, foam-filled triple-layer constructions, as a rule, the acoustic resistance of the outer layers is relatively less significant compared to the inner layer. The type of environment (whether it is isotropic or orthotropic) in each layer depends on the type and purpose of the material, but it is typically known in advance. Sometimes, for structural considerations, the construction's load-bearing capacity can be improved by adopting a cross-sectional scheme with a packet structure, where each packet (layer) is made of different anisotropic materials based on their specific properties. In such cases, determining acoustic parameters poses considerable difficulties. Therefore, experimental methods are often considered more suitable for determining the relevant acoustic parameters.

6. Multilayer Environment. The model for such an environment is more complex and is suitable for composite large-scale structures. In these constructions, various combinations of layers can be observed, such as: 1) all layers are isotropic and the bonded layers are anisotropic (the acoustic and physical-mechanical properties of the layers are the same); 2) all layers are anisotropic (the acoustic and physical-mechanical properties of the layers are the same); 3) a combination of isotropic and anisotropic layers (the distribution of acoustic and physical-mechanical properties is known and follows a certain rule).

In such an environment, the propagation parameters of elastic waves depend to a significant extent on the adhesion quality of all layers, the physical-mechanical and acoustic characteristics of each layer and the ratio of the wavelength of the elastic wave to the thickness of the layer.

4. Results

1. Analysis was conducted on the effective methods and reliability prediction for quality control of polymer composite materials (PCM). For this purpose, 8 factors were identified for the selection of the method and prediction of its reliability, taking into account the complexity of PCM control. In addition, low-frequency ultrasound, radio waves, infrared, optical, thermometric and electrical methods were recommended for the control of PCM and products made from it.

2. Models were selected for PCM and the products based on them to determine the effectiveness of applying low-frequency ultrasound equipment at the boundaries of controlled environments. This method allows the determination of the physical-mechanical, technological and structural parameters of the composition without distributing them. Additionally, the echo-pulse method is highly effective for such control.

3. The following models were selected for controlled environments for PCMs: 1) isotropic unidirectional environment; 2) transversely isotropic environment; 3) orthotropic environment; 4) combined bilayer environment; 5) triple-layer environment; 6) multilayer environment. The characteristics of each of these environments were analyzed separately.

4. Each of these environments, individually, finds its application in polymer composites, forming the scientific basis for quality control without distribution. In each of these environments, when the reinforcement filler is oriented in the longitudinal-to-transverse direction, the axes of elastic symmetry in the composite align vertically.

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