New approaches to diagnostics of quality of structures from polymeric composite materials under force and shock impact using the analysis of temperature fields

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Abstract. A rheological mathematical model that describes the process of formation of internal heat sources in a polymer composite material during its force loading, based on the process of microdestruction formation and the formation of dynamic temperature fields on the surface of the structure during thermal control, has been developed. The methodology as well as software and hardware for computer thermal control and diagnostics of the technical condition of complex spatial structures from PCM based on recording information about dynamic temperature fields have been developed and implemented. A thermal method has been developed for the quality control of composite armored barriers made of aramid materials through the study of the processes of its interaction in real time with a damaging element (kinematic, deformation, wave, thermal processes), which allows to increase the reliability of the quality of diagnostics, increase testing efficiency, visibility and objectivity of the results.

1. Introduction
Most structures made of composite materials are operated under conditions of force and shock loading. This determines the relevance of the development of methods for diagnosing the quality of structures in real test and operating conditions. One of the informative parameters of structures in the conditions of their testing and operation is the temperature field of the surface arising as a result of the processes inside the material. The article is devoted to the development of new methods for diagnosing the quality of structures made of polymer composite materials under conditions of force and shock impacts by analyzing temperature fields.

2. Methods, results and discussion
The development of equipment and technologies for creating products made of polymer composite materials (PCM) and ensuring safe operation of complex technical systems is impossible without the use of non-destructive testing methods and technical diagnostics [1–4].

The main requirement for complex structures made of composite materials is to ensure reliable operation in the process of applying existing loads to them and preserve the required performance characteristics.

Diagnostic methods are based on measuring indirect manifestations of damage occurring at the structural level of the material.
This paper discusses the possibilities of diagnosing the quality of structures operating at the most common loads: quasi-static power loads and dynamic shock loads by analyzing dynamic temperature fields.

Material microdamage seems to be quite acceptable during operation of the structure; it is known that their initial formation occurs at load levels several times lower than the limiting ones. On the other hand, the accumulation of microdamage is accompanied by the release of energy (acoustic, warm, electromagnetic), which makes it possible to detect zones in which these damages accumulate most intensively.

Firstly, it gives an opportunity to determine the places of stress concentration, potentially hazardous areas, and secondly to determine potential places of destruction of products, without bringing the products themselves to destruction.

The research results show that micro-destruction is accompanied by slight heating of the material by a value from fractions of a degree at the beginning of the process to several and tens of degrees close to destruction. Such temperature fields are recorded quite well by the thermal imager [5].

Another type of PCM actively used in personal protective equipment of armor personnel is created on the basis of fabrics from layers of high-strength fibers of various nature (aramid, ultra-high molecular weight polyethylene) having degrees of freedom of movement relative to each other. At the same time, increasing the safety of their properties is increasingly important.

The main element of the textile armored material is a fabric layer of complex yarns oriented in two mutually perpendicular directions and interconnected into a single whole due to mutual interweaving.

Confirmation of the protective properties of textile armor is carried out by its tests for penetration by a striking element, which determine the quality of the material, potentially dangerous weaknesses (structural units), worsening performance, which can lead to damage to personnel, and evaluate the level of technology for manufacturing armor.

It should be noted that the absorption of impact energy by armor-protective material occurs by two main mechanisms: due to irreversible deformation and due to friction during slipping (pulling) of the threads. According to the existing estimates, about half of the absorbed energy accounts for friction [6]. In this case, the irreversible deformation of the filaments is mainly localized near the contact of the striker and the armor, while slippage of the filaments and the accompanying energy losses due to friction take place in a wider zone.

Both irreversible deformation and friction of the threads lead to the release of energy in the form of heat. An increase in the temperature of the armored fabric can be detected by means of thermal control by high-speed shooting in the form of dynamic thermograms. The parameters of dynamic temperature fields, measured experimentally, can be used to verify and adjust theoretical and theoretical models, and the latter to estimate the amount of energy absorbed by different parts of the armored fabric at different distances from the place of impact. Such a calculation and experimental study can serve as the basis for assessing energy absorption in armor protection using various mechanisms and purposefully designing the structure of an armored package that will provide the greatest energy absorption.

Temperature measurement in the areas of interest, a joint analysis with the calculated data of the PCM deformation and fracture mechanisms made it possible to clarify the nature of the processes occurring in the object being tested and to predict its protective properties in the case of assessing the technical condition of the armored package and the strength properties of the product when diagnosing its behavior under power loading.

The construction of a mathematical model of such processes should ideally take into account the connectedness of the equations of deformation and heating [7].

The calculation of the stress-strain state of continuous media can be performed by a universal numerical method, for example, the finite element method [8]. A feature of the problem statement is to take into account the nonlinearity of the deformation diagram. The actual non-linear diagram should be obtained from material identification experiments. Since it is supposed to solve the conjugate problems of static deformation and thermal conductivity, it is advisable to use a software package [9].

An essential feature of textile armor is the presence of internal degrees of freedom [10], i.e. armor is not solid. In the process of inhibition of the damaging element, the initial structure of the tissue undergoes complex changes that occur in several stages.
It is accepted to distinguish the following stages of the interaction of the damaging body with textile armor [10]: tissue compaction in the facial layers, stretching and breaking of the threads, final inhibition with the formation of the back cone without breaking the threads. According to this view, the pulling of the threads occurs only at the last stage, and the deformation of the threads - at the second.

As it was noted in [11], the total fracture energy of the filaments can be significantly – 3–4 times lower than the energy of the damaging body, therefore, the shock interaction process should be considered in more detail. Nevertheless, the initial stage is the densification of the tissue and crushing of the fibers from transverse collapse, however, additionally, the fibers in the impact zone are welded into a monolithic formation. In the future, the process of penetration of the damaging body is of a wave nature, and very long volumes of tissue are involved in interaction. The stretching of the threads along the axis of their orientation, according to the representation [11], precedes their breaking from axial tension. In addition to the mentioned processes, at the final stage of breaking, the extension of the threads perpendicular to their orientation, the friction of the threads on the side surface of the striking body, the formation of a dent on the substrate (the body behind the barrier), as well as the irreversible deformation of the striking body, are also distinguished.

The analysis of the literature showed that the well-known models do not consider the thermomechanical properties and heating of woven materials upon impact. In this case, both irreversible deformation and friction of the threads lead to the release of energy in the form of heat, which is an indirect sign of the processes of deformation, fracture and slipping of threads occurring in the tissue. Heat generated leads to a rise in temperature; as mentioned above, in [11] experimental data on the heating of a woven barrier by 60 or more degrees are given. This effect can be used to indirectly estimate the energy absorption density in the volume of a woven barrier.

A promising method of non-destructive testing and PCM diagnostics is a rapidly developing thermal control (TC), where information about the parameters of the object is carried by the temperature of its surface, the values of which are mainly determined by the change in thermophysical, geometric characteristics and load parameters, as well as the state of the surface.

This method provides sufficient for practical use the reliability of the desired result [12, 13].

Since the temperature measured at the surface points of the controlled object, which is an indicator of the thermal processes occurring with it, is recognized as an information parameter in the TC, it is this method that allows studies of the deformation of structures from various materials, including from PCM occurring with the release of thermal energy.

A quantitative analysis of temperature fields with determination of the characteristics of the object being tested (geometric, thermotechnical, thermophysical) [2, 14, 15] using known technologies is based on calculation models related to solving direct and inverse heat conduction problems.

A new approach to thermal control technologies involves not only studying the mechanisms of heat transfer through the object being tested and applying design models of heat conduction, but considering all kinds of processes that occur in the structure when it is loaded with model and operational loads, up to failure.

Due to the fact that not all the energy received by the sample during power loading is converted into heat, we should first consider the model of heat release during the accumulation of damage in the composite material.

Research data [15] showed that with uniform deformation of PCM samples with a constant speed at the beginning, in the first stage, a small uniform heating of the sample occurs at 1 ... 2 ° C, with no visible damage being observed. Then, a visible macroscopic defect is formed (crack or delamination), and in this case the temperature field becomes substantially uneven: the temperature increase in the macroscopic fracture focus is about 10 ° C. This difference can be explained by the fact that in this zone the energy released as heat is stored as elastic energy in the entire test sample, while at the initial stage, the stored energy transfers to heat in the entire volume of the sample.

To build a model that quantitatively describes the first stage of heating during loading of the sample, we use the following assumptions.

1. The mechanical energy \( W_{\text{div}} \), irreversibly scattered during loading, is equal to the difference between the work of the loading force and the energy of elastic deformation of the sample:
where $u$ is the absolute elongation of the sample; $P$ is the tensile force; $K_0$ is the stiffness (the product of the cross-sectional area $F$ by the initial elastic modulus $E_0$).

2. Energy irreversibly dissipated during loading is expended on structural changes in the material and its heating, as well as on acoustic emission. The amount of energy converted into thermal $Q$ is estimated as a certain fraction of all the dissipated energy:

$$Q = b W_{dis},$$

(2)

where $b$ is the coefficient of the thermal effect of destruction, which will be considered constant.

3. Heat release occurs uniformly throughout the volume of the material and in the absence of heat exchange with the environment leads to a uniform increase in the temperature of the sample by the adiabatic increment $T_{ad}$ proportional to the value of thermal energy:

$$c \rho V T_{ad} = Q,$$

(3)

where $c$ is specific heat of the material; $\rho$ is density.

The coefficient of thermal effect $b$ is unknown in advance and must be identified. Therefore, along with the adiabatic temperature, it is also advisable to introduce a conditional temperature determined by the equality:

$$c \rho V T_{con} = W_{dis},$$

(4)

the released energy goes into heat.

If the temperature of the medium does not exceed the temperature of the sample, then the adiabatic temperature is the upper estimate of the actual temperature of the sample during the accumulation of microdamages, since it does not take into account the heat loss due to heat exchange with the environment. Conventional temperature, in turn, is the upper estimate of the adiabatic temperature.

Dividing equalities (1) - (4) by volume, we obtain similar ratios expressed in specific quantities:

$$w_{dis}(\varepsilon) = \int_0^\varepsilon \sigma(\varepsilon) d\varepsilon - \frac{1}{2} \frac{\sigma^2(\varepsilon)}{E_0},$$

(5)

where $w$ is the density of the scattered mechanical energy per unit volume; $\sigma$ is tension; $\varepsilon$ is deformation;

$$f = bw_{dis},$$

(6)

here $f$ is the bulk density of heat release, J/m$^3$;

$$c \rho V T_{ad} = f, \quad c \rho V T_{con} = w_{dis},$$

(7)

Figure 1 shows the type of approximating deformation diagram for organoplastics reinforced with TCR3 fabric on a bonding EDN-1U is shown in figure 1.

![Figure 1. A diagram for constructing an approximating function.](image-url)
The approximation of the deformation diagram contains four tuning parameters: the coordinates of the linearization points $\sigma^*$ and $\varepsilon^*$, the initial elastic modulus $E_0$ and the tangential elastic modulus $E_k$, which should be determined from experiments, from the deformation diagram. It is advisable to choose a linearization point in the third section of the diagram. The initial modulus of elasticity can be measured by unloading the sample. To calculate the approximation coefficients of the deformation diagram, a special technique and software have been developed.

The heat equation for a flat computational domain we will accept in the form:

$$
cp \frac{\partial T}{\partial t} = \lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + f - \frac{1}{H} h(T - T_\infty),
$$

where $\lambda_x$, $\lambda_y$ are the thermal conductivity coefficients along the $x$ and $y$ axes; $f$ is the intensity of heat generation, depending on the deformation and its speed; $H$ is the thickness of the sample; $T_\infty$ is the temperature of the medium.

Equation (8) must be solved with the initial condition:

$$
T(x, y, 0) = T_0
$$

and boundary conditions:

$$
T|_{B} = T_0,
$$

where $T_0$ is the initial temperature; $B$ is the boundary of the contact area with the grips of the testing machine, the temperature of which is constant and equal to $T_0$.

Applying the well-known discretization procedure by the weighted residual method we multiply both sides of equation (8) by temperature and integrate over the volume of the computational domain. We obtain the following integral equation:

$$
T(x, y, t) = \sum_i T_i(t) N_i(x, y),
$$

where $i$ is the node number of the finite element mesh; $T_i(t)$ is the temperature in the $i$-th node at time $t$.

From the deformations found, we find the heat release intensity. We believe that the thermal effect is determined by the dominant deformation $\varepsilon_x$, and taking this into account, we have:

$$
T_{ad}(\varepsilon_x) = 0.202 \cdot 10^4 bc_x^2,
$$

where coefficient $10^4$ takes into account that deformation is measured as fraction (not percentage).

The dependence of the calculated temperature on time was plotted for the points shown in figure 2: point 1 is in the center of the sample, point 2 is at the edge of the concentrator, and point 3 is at a distance from the concentrator.

The temperature calculated given the thermal conductivity of the sample was lower than adiabatic temperature; thermal conductivity losses for the considered sample shape were approximately 50%.

Areas of temperature increase with an average deformation of 1.5 to 2% are often not detected by the thermal imager, but become visible when deformation reaches about 50% of the limit.

In general, the calculated temperatures agree well with the measured ones. This allows us to conclude that the calculated normal temperature fields can be used as reference in determining the zones of accumulation of microdamage in flat structural elements from the studied organoplastics.

**Figure 2.** Location of points on the sample.
Figure 3. Dependence of temperature on time in the center of the sample ((a), at point 1), on the edge of the concentrator ((b), at point 2), away from the concentrator ((c), at point 3): solid line – thermal imager data, dotted line – calculation.

To identify the parameters of the model, a series of experiments was carried out on nine identical flat rectangular samples with a thickness of 4 mm, a width of 30 mm and a distance between the grips of the tensile testing machine of 155 mm. Samples were made of organoplastic reinforced with TCR3 fabric on a binder EDN-1Y.

Immediately before destruction, a small spot with a temperature of 2…3 °C higher than on the rest of the surface of the sample was observed (figure 5a). Then, failure occurred with a decrease in the force at the grips to zero and an abrupt increase in the spot temperature on the surface of the sample by 10...15 °C (figure 5b). With further cooling, the temperature gradually leveled off and decreased (figure 5c).

Figure 4. (a) – a photograph of the destroyed sample; (b) – an experimental setup.
Figure 5. Thermograms of the sample: (a) – 2 seconds before destruction; (b) – immediately after destruction; (c) – 40 seconds after destruction.

As a result of processing identification experiments, it was found that the dependence of the change in the adiabatic temperature on the strain is nonlinear. It can be described as a quadratic dependence of the form:

\[ T_{ad}(\varepsilon) = 0.202b\varepsilon^2. \]  \hspace{1cm} (13)

The value of the coefficient of thermal effect determined on this series of samples turned out to be 0.45. The coefficient \( b \) in the approximating dependence (13) is taken equal to 0.4.

Figure 6 illustrates the full-scale mesh test results.

Figure 6. Thermogram of the mesh structure under force load.

Experimental results show that the temperature of the ribs during loading varies slightly from 1 to 2 degrees up to the initial fracture, which can be seen on thermogram in the form of colored spots (figure 6b). The location of these spots – along the lower annular ribs – qualitatively corresponds to the calculation results.

The mathematical model for describing the energy release process during the interaction of rapidly moving penetrator with various layers of a multilayer armored barrier made of composite materials is based on averaging over the volume of physicomechanical and thermophysical characteristics of the woven material, which determine the identification parameters of the data of physical experiments. A rectangular layered woven sample is considered (figure 7). The object contains the following structural elements: a compliant base, a penetrator and a package of tissue layers, in which it is necessary to distinguish a separate zone of contact with PE.
Figure 7. A layered woven sample with a penetrator: 1 – penetrator, 2 – tissue layers, 3 – base.

Each layer is formed by two mutually perpendicular families of threads – weft and warp, and the angles between the direction of the warp and the edge of the sample in different layers can vary. The sample is on a flexible base. At the moment of impact, the central part of the sample is in contact with the penetrator, which mass \( M \) and initial velocity \( V_0 \) are known and are variables (parameters) that characterize the effects. In the process of interaction with the penetrator, it slows down.

In the process of interaction of tissue with the penetrator, it slows down; kinetic energy is converted to friction forces of the threads, causing structural changes and the destruction of the material of the threads, the irreversible stresses in the base and the heating of the sample, impactor and threads.

At the same time, state variables – the output parameters of the model – change in time: displacements \( U \), velocity \( \dot{U} \), internal stresses \( \Sigma \), and temperature \( T \). It is required to construct a mathematical model that displays the action variables \( \Xi = \{M, V_0\} \) on state variables \( \Psi = \{U, \dot{U}, \Sigma, T\} \):

\[
H = \Psi(\Xi).
\]

We decompose the model by processes (figure 8). For short, time derivatives are not shown: if the state parameter is the output variable of the mathematical model of the process, then its rate of change is also obtained from the same model.

Figure 8. Process interaction diagram.
The motion of a small mass element with an average density $\rho$ will be described by the equation of motion relating acceleration to density and acting stresses:

$$\ddot{U} = \dot{U}(\Sigma)$$

(15)

(the point hereinafter denotes the time derivative).

The input variables for the motion process are stresses, and the output variables are kinematic parameters (speeds and displacements) at the end of a sufficiently small time step. A change in the velocities and displacements leads to a change in the local kinematic parameters — strains $\varepsilon$ and strain rates $\dot{\varepsilon}$, including quantities characterizing the mutual slippage of the filaments inside the layer. A change in the kinematic parameters leads to a change in the stress state of the packet, which is due to deformation of the tissue layers and the mutual displacement of the threads in them:

$$\Sigma = \Sigma(\Sigma_0, \varepsilon, \dot{\varepsilon}, \omega),$$

(16)

where $\Sigma_0$ are stresses at the reference time, $\varepsilon_{ir}$ — are irreversible deformations.

Changes in deformations and stresses lead to the accumulation of irreversible deformations:

$$\varepsilon_{ir} = \varepsilon_{ir}(\Sigma, \varepsilon), \quad \dot{\varepsilon}_{ir} = \dot{\varepsilon}_{ir}(\Sigma, \varepsilon, \dot{\varepsilon}),$$

(17)

the power of stresses at irreversible deformation rates gives an increase in irreversibly dissipated energy $W_{ir}$:

$$W_{ir} = W_{ir}(\Sigma, \dot{\varepsilon}_{ir}).$$

(18)

This energy partially passes into heat, which causes a change in the adiabatic temperature of the material and leads to heat transfer due to heat conduction and heat transfer to the environment.

Using the developed mathematical model, theoretical studies of the possibility of thermal quality control of an armored obstacle in the process of interacting with a striking element were carried out in order to assess its energy absorbing ability.

Figure 9 (a, b, c) shows, as an example, the results of calculating the adiabatic surface temperature at various PE rates:

Figure 9 shows that in the latter case, the penetrator broke through the armor barrier and the temperature was localized in the central region.

Figure 9. Adiabatic surface temperature at initial speed: (a) –100 m/s, (b) – 200 m/s, (c) – 500 m/s.
Processing the results of theoretical studies allowed us to determine a number of dependencies that describe the process of interaction of the armored barrier and PE, which allows us to predict the characteristics of the studied structure. Figures 10, 11 show some of them as an example.

**Figure 10.** Dependence of the area of the threads involved in the interaction of the penetrator and the armored barrier on the speed of PE: \( V [m/s] \) – penetrator velocity, \( S / S^0 \) is the relative change in the area of threads, experimental results that coincide with the model, projected results.

Given the results of experimental studies the dependence in figure 10 allows predicting the maximum velocity of the penetrator for the studied multilayer armored obstacle (zero area means that the threads do not have time to absorb the penetrator energy).

**Figure 11.** Dependence of temperature \((T–25) \, ^{\circ}C\) in the region of filaments involved in the process of interaction with the penetrator on time after interaction.
The dependence in figure 11 makes it possible, knowing the propagation velocity of the heat front in the structure, to determine the occurrence depth from the surface of the armor layer that most efficiently extinguishes the penetrator energy with a velocity $V$. Such studies make it possible to arrange layers of a multilayer armored barrier in an optimal way for effective “damping” of the penetrator energy.

As a criterion for identifying the governing equations, the sum of the squares of the deviations of the calculated and measured temperature values at all selected points and for all time points (the “residual method”) recorded on the thermograms was selected. During identification, two factors varied - the temperature of the medium and the coefficient of thermal effect:

$$X(b, T_\infty) = \sum_i \sum_k [T_{calc}(t_k, b, T_\infty) - T_{ki}]^2,$$

where $i$ is the number of the point, $k$ is the number of time instant, $T_{ki}$ is the value of the measured temperature, $T_{calc}$ is the temperature value calculated by formula (20), $b$ is the coefficient of the thermal effect, and $T_\infty$ is the ambient temperature.

$$\frac{dT(t)}{dt} + 2 \frac{h}{c\rho H} T(t) = \frac{b}{c\rho} \sigma(\varepsilon) - \frac{\sigma(\varepsilon)}{E_0} \sigma' \frac{d\varepsilon}{dt} + 2 \frac{h}{c\rho H} T_c,$$

where $H$ is the thickness of the package, $h$ is the current coordinate of the thickness of the packet.

Based on the statistical processing of experimental data on the studied samples, the following was obtained: the average value of the coefficient of thermal effect was 0.0192, the standard deviation was 0.011.

The found coefficient of thermal effect allows us to calculate the adiabatic temperature at a known strain, based on the formula:

$$T_{ad} = \frac{bA}{c\rho}$$

is the adiabatic temperature (excluding thermal conductivity, due to internal heat release), where

$$A = \int_0^\varepsilon \sigma(\varepsilon) d\varepsilon - \frac{1}{2} \frac{\sigma^2(\varepsilon)}{E_{mod\text{un}}},$$

$\rho$ is the density of the material, $c$ is the specific heat of the material, $E_{mod\text{un}}$ is the unloading module.

Figure 12 shows typical thermograms of samples obtained during loading: (a) – at the initial time, before interacting with the penetrator, (b) – after 0.01 s after interaction, (c) – after 0.03 s, (d) – after 0.06 s (maximum temperature).

The data of experimental studies confirmed the previously made theoretical conclusions about the nature of the straining of threads depending on the speed of the penetrator: with an increase in the penetrator velocity to a certain limit, the area of the threads involved in the deformation increases, which allows selecting the appropriate material for the armor barrier; “Penetration” of the penetrator into the armor material was characterized by a sharp decrease in the area of deformed threads - they do not have time to deform and break through, etc. Studies have shown that the theoretical and experimental results are good enough for practical use – not more than 15%.
Figure 12. The temperature field of the surface of an armored barrier. The temperature on the thermograms varies from 220 °C to 133.80 °C. The temperature field was recorded with a FLIR X6530sc thermal imager with a frame rate of 146 Hz. Accuracy of temperature measurement ± 1 °C.

3. Conclusions

1. A rheological mathematical model that describes the process of formation of internal heat sources in a polymer composite material during its force loading, based on the process of microdestruction formation and the formation of dynamic temperature fields on the surface of the structure under thermal control has been developed. At the same time, the characteristic of irreversible energy dissipation under static loading with a constant deformation rate accompanied by a thermal effect was shown. To calculate the irreversibly dissipated energy, an approximation of the uniaxial strain diagram is proposed in the form of an exponential function that describes the decrease in the elastic modulus during deformation and the asymptotic approximation of the tangent modulus to a constant value.

2. The equipment and software and hardware for computer thermal monitoring and diagnostics of the technical condition of complex spatial structures from PCM was developed and implemented using the recording of information on dynamic temperature fields caused by the presence of stress concentrators (microdestruction), with information processing using specially developed methods and a program in power loading of controlled products.

3. A thermal method was developed for the quality control of composite armored barriers made of aramid materials based on the study of the processes of its interaction in real time with a damaging element (kinematic, deformation, thermal processes), which makes it possible to increase the reliability of quality diagnostics by 30...50 % and increase the efficiency of testing by several times, visibility and objectivity of the results.

4. A computer thermal control and diagnostic technique for technical composite armored barriers made of aramid fabrics based on registration of dynamic temperature fields during interaction with the damaging element and information processing using specially developed methods and a program was developed and implemented.
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