Ultra-jet diagnostics of functional-latent factors of composite materials

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Abstract. It is proposed to use a probabilistic modeling scheme to identify the role of latent factors influencing the functional parameters of products made from polymer composite materials. The principles in detection of latent factors are formulated, and the high efficiency of application of ultra-jet diagnostics technology for analyzing the significance of various structurally latent factors is shown.

Keywords: polymer composite material, ultra-jet diagnostics, latent influence factor, probabilistic model, identification principles.

1. Introduction

For the latent factor in the structure of an object of analysis (OA), we mean it’s physically implicit property and / or the hidden possibility to have a significant impact on the functional quality, for example, the performance of the operation of this OA.

As a rule, latent influence factors (LIF) are characteristic of technically and / or technologically complex systems, which include almost all types of composite materials (CM), primarily based on the polymer matrix - PCM. Figure 1 shows the block diagram of the classification of dominant LIF types in relation to quality analysis of PCM. A distinctive feature of this representation of LIF is the potential possibility of their identification and analysis through the use of the apparatus and tools of ultra-jet hydrophysical diagnostics (UJD) [1, 2], functional features of which are discussed in detail in a number of studies, in particular, in works [3-5].
2. Systematization of influence factors
Indeed, the physical and technological basis of the UJD is controlled minimally invasive, including step-by-step, hydro erosion local destruction of the surface layers of OA, for example, products made of PCM. According to the results of the analysis of the informative features of this physico-diagnostic influence, by studying the characteristic features of hydroerosion products, the factors influencing the specificity of this process are identified, including those having a structurally latent nature. In [6–9], it was shown that the informative parameters of the UJD are unambiguously related to the degree of damage to the surface layer of OA in the broad sense of the term, summarizing the results of the effect on OA of several, including dissimilar factors. It is the presence of a significant number of physicochemical, constructive-technological and other factors influencing the quality of PCM products, as well as the difficulty in forming functional interrelationships between explicit and latent state parameters of this class of OA, it is quite reasonably to suggest the effectiveness of using the probability theory apparatus to determine the required regularities between their input and output characteristics. To illustrate this point, we transform the phenomenological classification of LIF presented in Figure 1 into a block diagram of the functional interconnectedness of LIF presented in Figure 2 and which is quite a realistic base case for building the corresponding probabilistic model. Let us comment in more detail on some of the features of the interaction between the LIF, which are shown in this structural diagram.

![Figure 1](image_url)

**Figure 1.** Phenomenological classification of LIF and the role of UJD in their information identification.

![Figure 2](image_url)

**Figure 2.** A schematized version of the interaction of various LIF to build a probabilistic model for their analysis.
The initial internal block 1 is an illustration of the latent influence of the adhesion-cohesive factor (ACF) in the structural-elementary PCM cell, which has an initial probability of reliable operation with the required quality level, and the element reflects the positive influence of good adhesion between the PCM components: a filler and the binding media on this characteristic of operational and technological quality. The second block, by analogy with the first, takes into account both the positive, and negative latent influence of the residual stress factor in the PCM of a particular product on its functional quality. The third block of the structural scheme reflects, respectively, the negatively positive role of the scale factor (SF) of PCM products in the form of elements. The structural element parallel to the LIF interaction scheme examined in the form shows the conditionally unambiguous positive role of the UJD in the information and methodological support of the procedure for determining the characteristic probability values of the above-mentioned latent elements and blocks.

For example, for products, parts and other OA made from traditional PCM, the standard procedure for estimating the level and topography of the occurrence of residual stresses of the first kind by the classical Davidenkov method is practically impracticable. However, using a weakly invasive microfragmenting effect of ultra-jet (UJ) on the surface layer of OA, direct implementation of the engineering evaluation of the residual stress factor (RSF) using the Davidenkov method is possible. In addition, the dependence of the intensity of the UJ-hydroerosion process on the magnitude and sign of the residual stresses opens up a physically determined very potentially effective opportunity for the express analysis of information and diagnostic distinguishing features of the RSF.

3. Generalized probabilistic model

It should be emphasized that the effectiveness of the UJD for the identification and analysis of various LIF for typical and prospective PCM, depending on their physical and technological nature, will also be different. Nevertheless, by creating special conditions for conducting model comparative experiments, the necessary effectiveness of solving information technology tasks to identify the role of LIF is ensured [10-14]. Moreover, these experiments should be planned on the basis of the analysis of a specific, previously constructed model of interactions and functional features of one or several studied LIFs. For example, for an experimental study of the role of the latent adhesion factor, it is necessary, at a minimum, to change, in particular by screening, the level of adhesion between the fiber (filler) and the binder (matrix) with all other conditions of PCM formation being equal. Therefore, the success of the procedure for constructing a generalized model of accounting for the influence of LIF on the quality of PCM actually predetermines the purposeful effectiveness of planning and conducting experimental research, mainly of a comparative nature.

Based on this, we will form a probabilistic model of interaction between the three abovementioned LIFs: adhesive (ACF), residual tension (RSF) and scale factor (CF) strength (defectiveness) of the analyzed PCM, while not taking into account the roles of UJD in their identification. According to the block diagram presented in Figure 2, this probabilistic model will have the form:

\[
P = 1 - [(1 - (1 - p \cdot p_{n2})(1 - p_{n3})) \cdot p_{n3}] \cdot (1 - p_{n3})
\]

\[
p = 1 - (1 - p_{n1} \cdot p_{n2})(1 - p_{n1})
\]

where: \(P\) – total probabilistic assessment of the functional performance of PCM and / or products from it, taking into account the positively negative role of three types of LIF: ACF, RSF and CF.

Conventionally, in model (1) and its initial block, the role of the UJD is not taken into account in detail, which should actually be present in each of the analyzed blocks of the entire structural scheme. In particular, the role of UJD can be reflected in a generalized model of the form:

\[
P_0 = 1 - (1 - P)(1 - p_{n1})
\]

where: \(P\) – determined from (1) and (2), and \(p_{n1}\) – schematically shown in Figure 2.
We give a numerical example. Without a UJD, let the probabilistic assessment of the role of LIF, performed empirically, in particular according to the results of expert and analytical analysis to be \( P = 0.75 \). At the same time, the reliability of the UJD data factors is also equal to \( p_A = 0.75 \). Then the final assessment of the significance of LIF, according to (3) will be: \( P_0 \sim 0.94 \), i.e. the error in determining the role of LIF will not exceed 4%, which is quite acceptable in engineering calculations and the corresponding design and technological solutions.

Methodological interest is the analysis of any block from the standpoint of the neutral role of LIF in the formation of functional parameters of OA, in particular, products made of PCM. Using the example of block 1 (Figure 2), we determine the priority correlation between the positive and negative effects of the adhesion-cohesive factor in the PCM unit cell. For this, it is necessary to assume that the influence \( p_A1 \) and \( p_n1 \) is in fact of no effect due to their mutual functional annihilation and the final probabilistic assessment of the role of the analyzed LIF has not changed. Formally, this provision can be represented as:

\[
p = 1 - [(1 - p \cdot p_n)(1 - p_n)]
\]  \( (4) \)

where, to simplify recording, it is accepted \( p = p_0; p_n = p_n1; p_n = p_n1 \) (see block 1 in Figure 2).

For the detailed solution (4), it is logical to assume that the probabilities of the positive \( p_n \) and negative \( p_n \) effects of the latent adhesion factor form a complete group of events and their total probability is equal to one: \( p_n + p_n = 1.0 \). Then, taking into account this circumstance, the decision (4) relatively to \( p_n \) looks like:

\[
p_n = \frac{2p-1}{p}
\]  \( (5) \)

or for negative manifestations of LIF:

\[
p_n = \frac{1-p}{p} \cdot \quad (6)\)

And from (5) we can obtain an obvious restriction for \( P \):

\[
2p - 1 \geq 0 \cdot \quad (7)\)

The last relation physically means that with a small level of influence of source-dominant factors, i.e. when \( P < 0.5 \), it is practically impossible to balance the negative and positive manifestations of LIF. Thus, using the model of the system of interaction of an aggregate of LIFs by means of a targeted experimental and physical influence on it, the possibility is realized not only of assessing the role of individual factors in the overall picture of functional relationships, but also of their very likely synergistic manifestations. First of all, this provision refers to the structural-boundary effects of the physicochemical interactions of the matrix with the filler [15-20]. Moreover, the instrument and toolkit of the LIFs technology can become a tool for analyzing the surface structural manifestations of LIF, including synergistic ones.

4. Graphical illustration

As a typical example, Figure 3 provides a graphical illustration of an engineering methodology for rapid assessment of the level of residual stresses in the surface layer of OA, in particular products made of PCM. This technique organically combines the basic principles of UJD:
• the principle of the need for additional impact on the object of diagnosis in order to identify the analyzed LIF in accordance with its formalized description within a certain functional model;
• the principle of a relative comparison of the results of UJ-impact to OA, in particular the surface of the product from PCM, in “natural” conditions of operation and during model experiments;
• the principle of extrapolation of actually observed dependencies to the zone of determining the predicted value of LIF with hypothetically functional OA parameters.

![Figure 3](image_url)

**Figure 3.** Graphic illustration of the algorithm for determining residual stresses as a characteristic LIF.

In the figure it is accepted:

1. $J = f_1(\sigma)$ in the presence of reference value: $J_s = f(\sigma_{oct} = 0)$;
2. reference value $J_s = f(\sigma_{oct} = 0)$ is absent and dependence $J = f_2(\sigma)$ is built with functional latent participation of $\sigma_{oct}$;
3. $J_2, J_3, J_4$ – according to the intensity of the UJ-hydro erosion for the reference sample $(J_1, J_2)$ and the real OA $(J_3, J_4)$;
4. $\sigma_2, \sigma_3, \sigma_4$ – mechanical stresses OA from the action of additional power multi-level loads.

Designations are similar for $f(\sigma)$:

1. $J_0 = f(\sigma_{oct})$ – method of determination $\sigma_{oct}$ using dependency 1; $J_0 = f(\sigma_{oct})$ – the same, but for dependence 2;
2. $\Delta \sigma$ – error in the determination $\sigma_{oct}$ in the absence of data on UJD of the reference sample.

Conventionally, we denote these principles by the terms: complementarity (Д), comparability (C) with the standard and extrapolation (Э). These terms methodologically illustrate the UJ-algorithm for determining the level of residual stresses ($\sigma_{oct}$), presented in Figure 4.
Figure 4. Graphic illustration of the method for express determination of structural damage $\omega_c$ of various PCM as a significant LIF.

In the figure it is accepted:

- equality of total UJD impact DCR $F_{12}$ and $F_{21}$;
- $R_1$ and $R_2$ - respectively, the results of exposure $F_{12}$ and $F_{21}$;
- $\Delta R$ and $\Delta \omega_c$ - respectively, the information-significant difference in the results of UJ-impact and structural damage of PCM.

A distinctive feature of this algorithm are two options for the definition: more accurate – in the presence of a reference OA sample with a conditionally zero level and only real OA, for which the assumption is a priori:

$$\sigma_{\text{act}} < \sigma_{\text{pact}}$$

where $\sigma_{\text{pact}}$ – additional tensile stresses created in the conditions of a model experiment on the UJD of a sample of PCM or another material when it is significant multi-level tension by external force.

5. Conclusions

The above example of defining the role of LIF in the form of residual stresses in the structure of PCM clearly illustrates the information and diagnostic capabilities of the formulated principles of their functional identification. To identify other LIFs, such as the factor of physical and technological heredity and / or operational damage (defectiveness) of OA material, these principles should be supplemented with the following provisions:

- the principle of non-commutativity of the results of consecutive-variable UJ impacts of the so-called K-principle of nonlinear diagnostics;
- the principle of performance of physical analogies of the additional impact - the principle - A, according to which the level of the most diverse influences on the PCM can be formalized along the abscissa axis: thermal, radiation, etc.

Schematically, Figure 4 illustrates the methodically feasible possibility of detecting LIF in the form of damage to the surface layer of a PCM product. The distinctive feature of this technique is comparing the results of 2 different-level effects in the analysis of which the functional potential of the K-principle is used to obtain comprehensive information about the damage (defectiveness) of an OA surface during its UJD.

Thus, the use of probabilistic modeling apparatus of the role of LIF in the formation of the output characteristics of products from PCM allows for quite effective information verification of the
proposed models through the targeted application of UJD tools and the corresponding principles of identification analysis.

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