ASPECTS OF THE STUDY OF MOISTURE TRANSFER IN COMPOSITE MATERIALS WITH THE HELP OF X-RAY COMPUTATIONAL TOMOGRAPHY

V. I. Barakhov, V. A. Chernyaeva,
V. S. Kiselev, and A. P. Stepanov

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Questions associated with the assumptions employed in x-ray computational tomography, the choice of data processing regime, and the thickness of the scanned layer are studied.

Computational tomography is now one of the most promising methods for studying the internal structure of the materials of manufactured parts and its nonuniformities, detecting defects, and studying different physical processes. The distinguishing feature of this method is that it permits evaluating the densities of separate elementary cells of the material without destroying the wholeness of the material. This is made possible by the fact that the tomograph enables, by means of scanning and reconstruction of images, the reconstruction of complex pictures of the internal structure of composite materials, determining the linear coefficient of attenuation (LCA) of each elementary cell f_{ij} of the cross section studied. The matrix of values of the LCA $F(f_{ij})$ can be converted into the matrix of the density $P(\rho_{ij})$. Thus the use of a tomograph in the study of physical processes makes it possible to observe the change in $P(\rho_{ij})$ for a fixed cross section of the material as a function of time.

One of the promising areas of application of x-ray computational tomography is the study of moisture transfer in composite materials. The conduct of work in this field has some characteristic aspect associated with the specific nature of tomographic measurements, determined by the interaction of the x-ray radiation with the material and the mathematical processing of the scanning data.

All methods of reconstruction in x-ray computational tomography are based on a number of simplifying assumptions, primarily that the attenuation of the collimated monochromatic flux of the radiation by the material of the part is exponential. The mathematical problem of computational tomography reduces to solving an integral equation of the first kind

$$\iint\limits_{-\infty}^{+\infty} f(x, y)\,\delta(x\cos\varphi + y\sin\varphi - r)\,dxdy = P(r, \varphi) \tag{1}$$

and reconstructions the length-bounded, two-dimensional distribution of LCA $f(x, y)$ from the given linear projections $P(r, \varphi)$. They are evaluated experimentally with errors that have both random and systematic components [1], The physical properties of the x-ray radiation employed, with regard to the errors in $P(r, \varphi)$, are manifested primarily in two aspects [2]: the nonmonoenergetic nature of the radiation employed, the effect of the scattered radiation and the finite width; and quantum nature of the radiation employed.

One question in the study of moisture transfer in composite materials by the tomographic method involves the mathematical processing of the scanning results. The tomograph has several data processing modes, characterized by convolution and inverse projection procedures. Weighting coefficients are introduced for given scanning profiles, whose level is determined by the selected convolution kernels. The convolution kernel affects the visualization of the details of the studied cross section of the material. Figure 1 shows tomograms of one and the same cross section of an organic plastic, reconstructed in the BAL and H1 modes. One can see from Fig. 1 that the pictures (and hence the matrices of the values of LCA also) differ somewhat. For this reason a data processing regime that is not well founded can lead to additional errors in the determination of the characteristics of the process under study.

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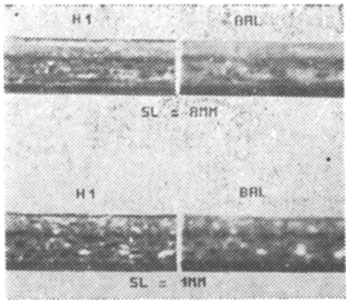

Fig. 1. Tomograms of the transverse cross section of organic plastic. The tomograms were obtained by reconstruction in the BAL (balancing) and H1 (high resolution) modes with the thickness of the scanning layer SL = $1 \cdot 10^{-3}$ m, SL = $8 \cdot 10^{-3}$ m.

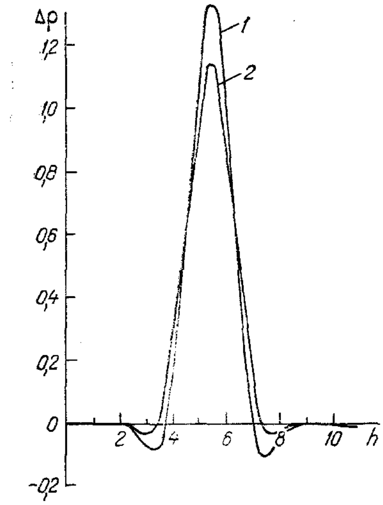

Fig. 2. Curves of the change in the density of the material $\rho \cdot 10^{-3}$ kg/m^3 over the thickness $h \cdot 10^{-3}$ m in the zone of the opening, obtained by processing the subtraction matrices of the LCA of sections with and without water: 1) for the H1 mode; 2) for the BAL mode.

A comparative experiment on a wax sample with an opening was employed to select the data processing regime. Water was poured into the opening. The water mass was determined by weighing and tomographic measurement of the sample without and with water. Figure 2 shows the results of the tomographic measurements in the form of curves of the change in the density of the cells in the zone of the opening for LCA matrices obtained by subtraction from matrices of the LCA for the cross section with and without water in different regimes for processing the scanning data. Comparison of the measurements of the water mass in the opening by weighing ($6.8 \cdot 10^{-5}$ kg) and by tomography ($6.2 \cdot 10^{-5}$ kg) showed that the H1 mode gives the closest result. The tomographic data in this case were processed taking into account the edge effect (Fig. 2). The H1 mode was employed to study moisture transfer in organic plastics.

Another important feature of the study of moisture transfer in composite materials is the choice of the thickness of the scanning layer SL. It can assume the values SL = $(1; 2; 4; 8) \cdot 10^{-3}$ m. Figure 3 shows tomograms of the same transverse cross section of the sample of organic plastic with water on a surface scanned with SL = $2 \cdot 10^{-3}$ m and SL = $8 \cdot 10^{-3}$ m. As one can see from Figs. 3a and b the reconstruction with SL = $2 \cdot 10^{-3}$ m has the highest contrast. The histogram of the distribution of the LCA here has the greatest width and is characterized by a high standard deviation ST = 94.5, though the mathematical expectations (ME) for the reconstructions are close. The spread in the values is lowest for the reconstruction with SL = $8 \cdot 10^{-3}$ m (ST = 72.8). Figures 3c and d show the reconstruction, made using the image subtraction operation, of the same cross sections after water permeated over a period of $t \approx 1590$ sec through the sample. The starting image was subtracted from the

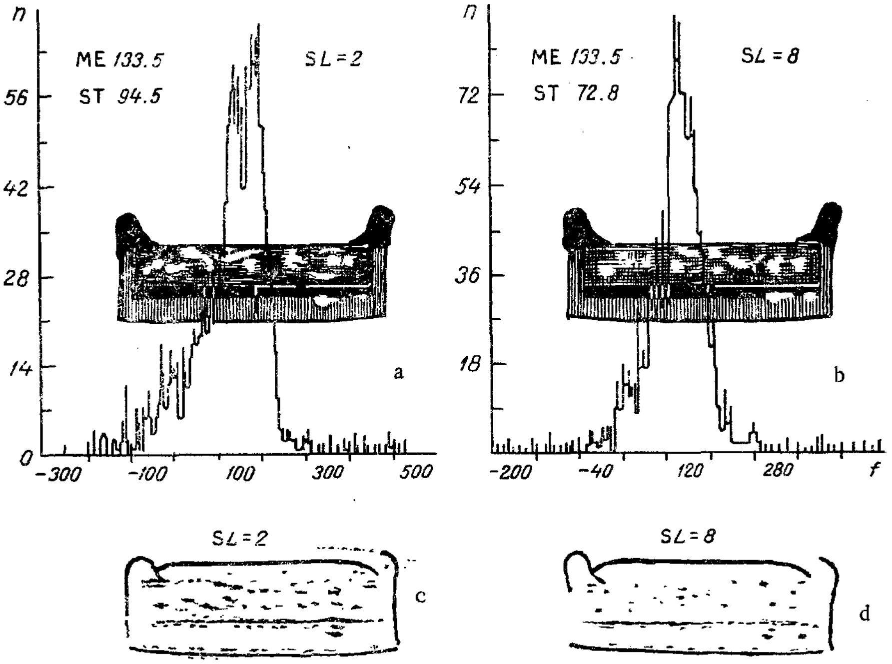

Fig. 3. Tomograms of a sample of organic plastic with water on the surface, obtained by scanning with a layer thickness SL = $2 \cdot 10^{-3}$ m and SL = $8 \cdot 10^{-3}$ m: a, b) histograms of the distribution of the LCA f of the cross section in the starting state of the material; n is the number of cells; c, d) subtraction tomograms, showing the permeation of water in the transverse cross section of the composite material over period of 1590 sec.

final image. The white inclusions characterize the permeation of water through the thickness of the sample. As one can see from Figs. 3c and d, the clearest picture of the permeation is obtained for scanning with a layer thickness SL = $2 \cdot 10^{-3}$ m. Thus here there arises the problem of choosing the optimal thickness of the scanning layer.

In performing prolonged experiments on the saturation of composite materials with moisture with periodic scanning there arises a problem associated with the error in the placement of the samples for tomography of one and the same section. Figure 3 shows that the study of moisture transfer in organic plastics is best performed with minimum SL. This gives the maximum information about the process, but also the maximum placement error.

To choose the optimal thickness of the scanning layer, in the case under study, we can employ the information approach with the criterion of average risk. Because of the random character of the elements of the matrix $F(f_{ij})$ the composite-material—moisture system is indeterminate. In information theory a characteristic called the entropy is employed as a measure of a priori indeterminateness of a system:

$$H(f) = \int_{-\infty}^{+\infty} \xi(f) \log[\xi(f)]\, df = M\{-\log[\xi(f)]\}. \quad (2)$$

The increment to information obtained by replacing SL_i by SL_{i+1} can be defined as follows:

$$\Delta I = H_{i+1}(f) - H_i(f). \quad (3)$$

Investigations show that in this case to calculate H(f) it is sufficient to employ two distribution laws $\xi(f)$: normal and Weibull. For them

$$H(f) = \log(\mathrm{ST}\sqrt{2\pi e}); \quad (4)$$

$$H(f) = \log\left[1 + \frac{\alpha - 1}{\alpha}(e + \ln\beta)\right] - \log\alpha\beta; \quad (5)$$

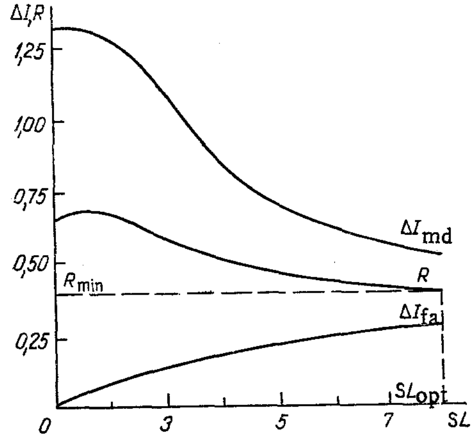

Fig. 4. Results of determining SL_{opt} [m] for one of the samples or organic plastic; ΔI, R_{nit}.

$$\Delta I = \log \frac{ST_{i+1}}{ST_i};\tag{6}$$

$$\Delta I = \log \left[\frac{C(\alpha_{i+1} - \alpha_i) + \ln \frac{\beta_i^{\alpha i+1}}{\beta_{i+1}^{\alpha i}}}{\alpha_{i+1}\alpha_i} + \ln \frac{\beta_{i+1}}{\beta_i} \right] + \log \frac{\alpha_i \beta_i}{\alpha_{i+1}\beta_{i+1}},\tag{7}$$

where $\beta = (1/\Theta)^{\alpha}$.

We shall regard the error (ΔG) in the determination of the quantity of moisture permeating into the material as a random quantity. It is a continuous random variable, distributed according to the law f(ΔG). In setting the optimal layer thickness we can assert with a probability of a reliable event P(A) = 1 that we make an error: either we miss the defect or we have a false alarm. The problem consists of determining the thickness of the scanning layer that minimizes the error in determining the amount of moisture permeating into the sample. For the criterion of optimality we choose the average risk [3]

$$R = C_{21}P(H_{21}) + C_{12}P(H_{12}),\tag{8}$$

$$P(H_{21}) = \int_0^{\infty} f(\Delta G)\, d\Delta G;\ P(H_{12}) = \int_{-\infty}^{0} f(\Delta G)\, d\Delta G.\tag{9}$$

The values of the errors must take into account the assumed consequences of a false alarm and of missing a defect. We shall study the situation in which we make a transition from a layer with thickness SL_{i+1} to SL_i, where $SL_{i+1} > SL_i$. Two cases are possible here. The first case occurs when the precision of placement did not change (false-alarm situation). Then from this transition we obtain the increment to information (ΔI_{fa}) (4)-(7). Here $(C_{21})_i = (\Delta I_{fa})_i$. In the second case a placement error appears (the situation when a defect is missed). With a nonzero placement error, i.e., missing a defect, we increase the entropic interval of uncertainty $l = 2\Delta$ [4], where Δ is the instrumental error of the measurement results. Since the amount of information obtained as a result of the measurement equals the difference of the starting and remaining entropies, i.e.,

$$I = \ln \frac{x_2 - x_1}{2\Delta},\tag{10}$$

the information increment owing to missing of a defect will be given by the formula

$$(\Delta I_{md})_i = \ln \left[1 + \frac{(\Delta y)_i}{(\Delta)_i} \right].\tag{11}$$

The importance of missing a defect is $(C_{12})_i = (\Delta I_{md})_i$. The optimal layer thickness corresponds to minimum average risk $SL \to R_{min}$. The results of determining SL_{opt} for one of the samples of organic plastic are presented in Fig. 4. The studies showed that the optimal thickness of the scanning layer in studying moisture transfer in composite materials $SL = 8 \cdot 10^{-3}$ m. The placement error, which for $SL = 8 \cdot 10^{-3}$ m is minimum, has the greatest effect on the result here.

Thus in studying moisture transfer processes in composite materials by the tomographic method some noise level must be taken into account, and the choice of the data processing regime and the thickness of the scanning layer must be approached in a well-founded manner.

NOTATION

$\xi(f)$, distribution of the random variable f; e, base of the natural logarithm; α, shape parameter; Θ, scale parameter; C = 0.5772, Euler's constant; C_{21}, value of a false alarm; C_{12}, importance of missing a defect; $P(H_{21})$, $P(H_{12})$, probability of a false alarm and the probability of missing a defect; Δ, instrumental error; $x_2 - x_1$, range of uncertainty prior to the measurements; $(\Delta y)_i$, increment to the entropy interval owing to the placement error.

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MODELING OF RESERVOIRS IN A BAZHENITE SUITE

Yu. A. Buevich and V. A. Ustinov

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The characteristic features of a structural model of bazhenites, regarded as a collection of horizontal layers, which are formed by a system of overlapping, permeable, lenslike cavities in an impermeable medium, are discussed.

1. Commercial pools of petroleum in the sedimentary deposits of a bazhenite suite are the most promising formations for increasing the reserves of petroleum in the West-Siberian region. The problem of estimating these reserves and developing corresponding computational methods is therefore of great interest. Since bazhenites have a number of unusual properties that distinguish them significantly from other well-known reservoirs, to solve this problem it is first necessary to construct an adequate structural model of bazhenites and the character of the petroleum distribution in them.

Based on modern ideas [1] petroleum-bearing regions in bazhenites are concentrated in permeable, lens-like cavities, oriented parallel to the stratification and occurring in dense, impermeable rocks. In addition, significant, large-scale nonuniformity occurs in both the horizontal and vertical directions. Vertical sections of separate wells reveal permeable intercalations differing in thickness and filtrational characteristics. The sizes and properties of the cavities (lenses) in the same horizontal layer can also vary over a wide range.

These structural features of a reservoir in a bazhenite suite lead to the fact that its global characteristics as a fluid-conducting medium are very unusual. This makes many

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