DETECTION OF LAYERS WITH A HIGH CONCENTRATION OF MICROCRACKS IN CARBON-BEARING COMPOSITES BY THE EDDY-CURRENT METHOD

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The fracture of composites is a complex, multistage process which begins long before final rupture. The rate of fracture differs significantly in different sections of a loaded body. As a result, the process may be completed on a certain section but on other sections may have only reached a certain stage — a stage which might be quite far from final rupture [1, 2].

An increase in the concentration of submicrocracks formed as a result of ruptures of interatomic bonds increases the probability of their merging and the formation of microcracks that will destroy the reinforcing fibers. This process occurs most intensively in the surface regions of the loaded body, and it is here that it is natural to expect the presence of concentration nonuniformities in different sections [1].

Submicrocracks in oriented films of crystalline polymers are best detected by the method of low-angle x-ray diffraction. Some researchers make more frequent use of the methods of acoustic emission, recording of changes in the mechanical characteristics of the material, and direct microscopic analysis to detect microscopic defects in bodies. A very convenient indicator of the process of fatigue damage accumulation in composites is heating to a low temperature (such as 20°C). Such heating has little effect on the fatigue resistance of the material [3].

The electrical resistivity of a material — as its thermal conductivity — depends on the concentration of fiber ruptures. This dependence is in fact a prerequisite for use of the eddy-current method of flaw detection. The latter method has already been successfully used to study the structure of composites (see [4-7], for example).

The methods used to detect macrocracks in carbon-bearing composites [8, 9] are based on an abrupt change in the path of eddy current in the region of a defect due to the formation of a continuous layer of air in its path. The presence of microcracks — which rupture fibers and thereby loosen the given material [10] — leads to a decrease in the conduction of electricity in the region of macrodefect formation. In this case, there is little change in the path of the eddy current.

The following expression [11] determines (with an error no greater than 2-3%) the density of an eddy current induced by the field of a short cylindrical coil (eddy-current transformer) with the radius R_1 and number of turns W in a conducting nonferromagnetic half-space:

\[ j = -\frac{1}{4\pi^2} I W \lambda (3\pi - 10) \sqrt{\frac{R_1}{\rho}} e^{-\frac{3h}{2R}} \sqrt{\frac{\lambda^2 + i\omega\sigma_0 - \lambda}{\lambda}} e^{-\frac{\sigma_0}{2\pi R_1}} , \]

where I = I_0 e^{i\omega t} is the current in the winding of the eddy-current transformer (ECT); \( \lambda = 3/2R \) (R is the larger of R_1 and \( \rho \)); \( x = \rho/R_1 \) at \( \rho/R_1 \leq 1 \) and \( x = R_1/\rho \) at \( \rho/R_1 > 1 \); \( \rho \) and \( z \) are the axes of the cylindrical coordinate system (the origin is located at the intersection of the axis of symmetry of the coil and the surface of the half-space, while the \( z \) axis is directed into the depth of the material); \( h \) is the distance from the outermost turn of the coil to the surface of the material; \( \sigma \) is the electrical conductivity of the composite material; \( \mu_0 = 4\pi \cdot 10^{-7} \) H/m.

We will assume that size of the gap \( h = 0 \). The modulus of eddy-current density \( j \) normalized with respect to the product IW will be represented as follows:

\[ \text{in the region } \rho \leq R_1, \quad j = \frac{\lambda}{4\pi^2} \sqrt{(A - \lambda)^2 + B^2} e^{-A_z} \left( 3\pi \sqrt{\frac{\rho}{\rho_0}} - \frac{10}{\sqrt{\rho_0}} \right) , \] (1)
Fig. 1. Eddy-current density distribution when $\omega \mu_0 = 10^5$ (1); $10^6$ (2); $10^7$ 1/m$^2$ (3).

where $\bar{\rho} = \rho/R_1$, $\Lambda = 3/2R_1$;

$$j = \frac{\Lambda}{4\pi^2} \sqrt{(A-\lambda)^2+B^2} e^{-\Lambda z} \left( \frac{34}{\rho^{1/2}} - \frac{10}{\bar{\rho}} \right),$$

where $\lambda = 3/2\rho$; $A = \sqrt{\lambda^2 + \omega^2 \mu_0 \sigma \cos \varphi/2}$; $B = A \tan \varphi/2$; $\varphi = \arctan \left[ (\omega \mu_0) / \Lambda \right]$.

The maximum of the eddy-current density is located directly under the turn of the ECT and is determined from (1-2) with $\rho = R_1$ and $z = 0$:

$$j_0 = \frac{24\Lambda}{4\pi^2} \sqrt{(A-\lambda)^2+B^2}.$$

By limiting $j$ to the level $0.1j_0$, we find the boundary of the cross section of the current tube:

$$z = \frac{34\bar{\rho} - 10}{2A \bar{\rho}}.$$

Figure 1 shows these sections for different values of $\omega \mu_0$ ($z = z/R_1$, $R_1 = 2 \cdot 10^{-3}$ m).

We now find the eddy current:

$$I_0 = \frac{1}{\Lambda} \ln \frac{34\bar{\rho} - 10}{2A \bar{\rho}} + \frac{1}{10} \int_0^{\Lambda} \bar{j}_2(\rho, z) d\rho + \frac{1}{10} \int_0^{\Lambda} \bar{j}_3(\rho, z) d\rho,$$

where $\bar{j}_2$ and $\bar{j}_3$ are determined by Eqs. (1) and (2), respectively. After integration, we obtain

$$I_0 = 15.4 \frac{\Lambda}{4\pi^2} \sqrt{(A-\lambda)^2+B^2} I_0.$$

Remaining within the cross section of the eddy-current tube, we locate the vertical axis of a layer with a conductivity $\sigma_d$ less than the conductivity $\sigma$ of the base material. We designate the boundaries of the layer along the axis $\bar{\rho}$ as $\bar{\rho}_1$ and $\bar{\rho}_2$, $\Delta \bar{\rho} = \bar{\rho}_2 - \bar{\rho}_1$. In the depth of the material along the $z$ axis, the layer is bounded by the common boundary of the section (deep anomalous layer).