DETERMINATION OF THE DISPLACEMENT VECTOR AT THE CRACK TIP FOR COMPLEX KINDS OF LOADING BY THE USE OF HOLOGRAPHIC AND SPECKLE INTERFEROMETRY

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The majority of structural elements and machine parts are operating in the conditions of complex mechanical and temperature effects. In addition, the complex stress-strain state (SSS) occurs in the vicinity of tips of the possible crack-like defects. The fracture initiation under these conditions at elastic-plastic behavior of the material is determined by three components of the displacement vector $\vec{\delta}$ (δ_I, δ_{II}, δ_{III}) at the crack corresponding to three modes of deformation: δ_I – opening, δ_{II} – sliding, δ_{III} – tearing.

In other words there is a closed fracture surface

$$f(\delta_{Ic}, \delta_{IIc}, \delta_{IIIc}) = 0,$$

determined by the vector of displacement $\vec{\delta}$ (δ_{Ic}, δ_{IIc}, δ_{IIIc}). It establishes the limiting state of the material with a crack in the conditions of the complex loading.

For the prediction of the fracture initiation of the structural element it is necessary to have available the current values of parameters SSS δ_I, δ_{II} and δ_{III} (they are defined by the shape, sizes and kind of the element loading, type, sizes and orientation of the defect in the field of stresses) and critical δ_I, δ_{II} and δ_{III}, determining the fracture surface in the appropriate temperature conditions of service. At the same time the number of such data is now rather limited due to the difficulties occuring at the physical statement and mathematical realization of the problems of mechanics of the quasi-brittle fracture of the three-dimensional bodies with cracks, as well as a lack of a universal methodology and instruments for carrying out the experimental studies. As to the theoretical solution of the abovementioned problems, then, the δ_κ – model is very effective, reducing the elastic-plastic problems to the corresponding problems of the mathematical theory of elasticity [1, 2, 3]. The calculated scheme of the local fracture, as well as its realization in the solution of the definite problems, formulated on the base of the δ_κ – model was a new step in the solution of the elastic-plastic problems [4].

In the present work the scheme of measuring and calculation of the displacement vector at the crack tip for complex kinds of loading is considered on the basis of the methods of the holographic and speckle interferometry. The suggested methods permit to experimentally set the current (δ_{Ic}, δ_{IIc}, δ_{IIIc}) and critical (δ_{Ic}, δ_{IIc}, δ_{IIIc}) values of SSS parameters for the bodies of the random configuration with cracks propagated to the surface. The latter are the initial data for the surface construction accounting for changing the mechanism of the local fracture typical for the majority of the structural steels. This, in turn, will serve as the base for a thorough study of the process of fracture of materials of the complex loading, justification of the criteria of the fracture initiation and determination of the transition conditions from one type of the local fracture to the other.

The speckle interferometric methods [5,6] are based on the double-exposure record of the speckle-structures (laser speckle pattern) in the plane of the optic system. The light waves, reflected from the surface of the examined structure, modulated by the speckle-structures, are capable of reproducing its three-dimensional spectrum in the initial and displaced state, thus permitting to obtain the speckle interferograms, providing the information about the value and mode of changes, to which the structure was subjected. The period of the observed fringe pattern is determined by the value of the object displacement Δr, that permits easy calculation of the values of displacement by measuring the period of fringes D,

$$\Delta r = \lambda L / MD,$$

where : M is the magnification of the optic system; λ is the length of laser radiation wave, L is the distance between the photoplate, on which the speckle-interferogram is recorded, and the recording screen. Here, the components of the displacement vector are determined as follows:

$$u = \Delta r \cdot \sin\theta, \; v = \Delta r \cdot \cos\theta,$$

where : θ is the angle of inclination of fringes to the OX axis.

To determine the crack face opening one should consider the crack at two successive stages of deforming (Fig.1) in the Cartesian system of coordinates OXY. Let us assume that the points A and B with coordinates X_A, Y_A, and X_B, Y_B (known in the given system) were displaced into points A′ (X'_A, Y'_A) and B′ (X'_B, Y'_B). Their coordinates are calculated by the formulae:

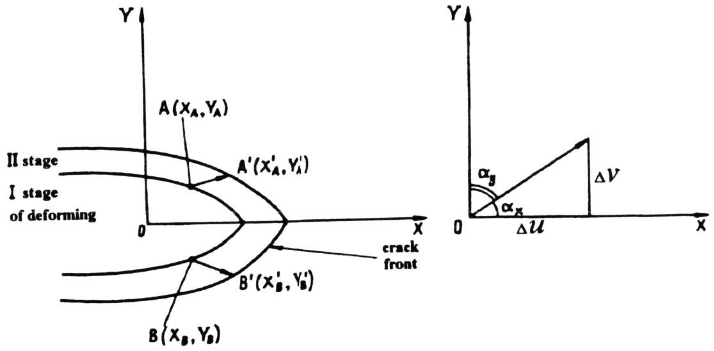

Fig. 1. Scheme of crack opening

$$\begin{cases} X'_A = X_A + \overline{AA'}\,x, \\ Y'_A = Y_A + \overline{AA'}\,y, \end{cases} \qquad \begin{cases} X'_B = X_B + \overline{BB'}\,x, \\ Y'_B = Y_B + \overline{BB'}\,y, \end{cases}$$

where $\overline{AA'}_x$, $\overline{AA'}_y$, $\overline{BB'}_x$, and $\overline{BB'}_y$ are the projections of vectors of displacement of points A and B on the axis of coordinates OX and OY, respectively.

For the components of the vector of displacement u and v determined experimentally by the method of the speckle interferometry the following correlation is established:

$$\begin{cases} u_A = \overline{AA'}\,x, \\ v_A = \overline{AA'}\,y, \end{cases} \qquad \begin{cases} u_B = \overline{BB'}\,x, \\ v_B = \overline{BB'}\,y, \end{cases}$$

The resulting vector of opening is $(\overrightarrow{A'B'} - \overrightarrow{AB})$, at the initial moment being $\overrightarrow{AB} = \vec{0}$ $\overline{AB}_x = 0$, $\overline{AB} = 0$. The projections of the resulting vector on the axis of coordinates OX and OY:

$$\overline{A'B'}_x = \overline{BB'}_x - \overline{AA'}_x = u_B - u_A = \Delta u,$$

$$\overline{A'B'}_y = \overline{BB'}_y - \overline{AA'}_y = v_B - v_A = \Delta v.$$

Thus, the crack opening (the length of the resulting vector) is determined by the expression: $\Delta\delta = \delta_B - \delta_A = \sqrt{\Delta u^2 + \Delta v^2}$.

The angles of inclination of the resulting vector to the axes of coordinates

$$\alpha_x = \operatorname{arctg}\frac{\Delta v}{\Delta u} \text{ and } \alpha_y = \operatorname{arctg}\frac{\Delta u}{\Delta v}.$$

In our studies the scheme suggested by Leendertz, was selected for the speckle-interferometric determination of the fields of displacements in the elements of the welded structures at the presenceof the stress raiser (Fig.2) [7]. Such scheme permits to determine the displacements of u and v, characterising the defect opening with an accuracy of approx. 1 μm and to avoid the effect of normal displacements of the structure being examined, caused by its rigid displacement. As a result of the carried out experiments for the scheme optimizing the following parameters were selected: β = 45°, d_1 = 50 mm and d_2 = 150 mm.

In the developed model of the speckle-interferometer the objective with a 50 mm focus distance and a 35 mm diameter of the aperture was used. A helium-neon laser with a wave length λ = 0.63 μm was used as a source of radiation. It was fastened to its own base not rigidly connected with the board on which the holographic scheme was assembled. This was possible due to the application of the method of the speckle-interferometry characterized by the low requirements to the rigidity of the elements of the optic system (as compared to the methods of the holographic interferometry). The dimensions of the designed small-sized holographic unit was 450X350X300 mm.

By the application of the developed method and the model of the speckle-interferometer the studies of the fields of displacement in the elements of the welded structure having cracks were carried out. As objects of the examinations the specimens of the welded joints with the crack-like defects of length l were used

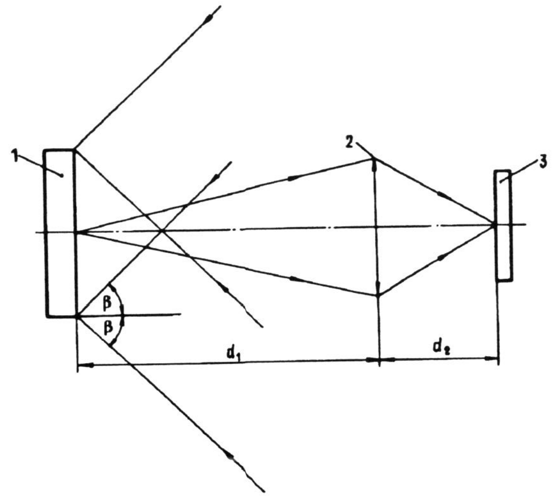

Fig. 2. Optical scheme of speckle interferometer: 1 – object being examined; 2 – objective; 3 – recording plate.

(Fig. 4 a). The examined specimens were subjected to three-point bending. On loading the specimen till fracture the two-exposure speckle-interferograms of the zone of the artificial crack on the low-carbon steel recorded in steps.

Two series of the specimens were tested: one with a fatigue crack, initiated at the tip of the mechanical notch (1.5 mm width) and one with a thin saw cut of less than 0.04 mm near the tip. The opening of the crack tip was determined with the help of the method of the speckle interferometry and special two-console gauges of the tensoresistor type. The calculation of δ value by in-test measured displacements of the crack faces V_1 and V_2, respectively, at the distances a_1 and a_2 from its tip was carried out by the formula:

$$\delta = \frac{V_1 a_2 - V_2 a_1}{a_2 - a_1}.$$

The speckle interferogram of the crack zone was recorded on the high-resolution holographic plates with 2 s time of exposure. After developing and scanning of the photoplates by the non-split laser beam the interferogram was displayed on the screen (system of the interference fringes) characterizing the deformations in that point through which the laser beam passed (Fig. 3). Thus, by illuminating different zones of the welded joint specimen being examined (Fig. 4 a) the interferograms characterizing the deformations in them were observed.

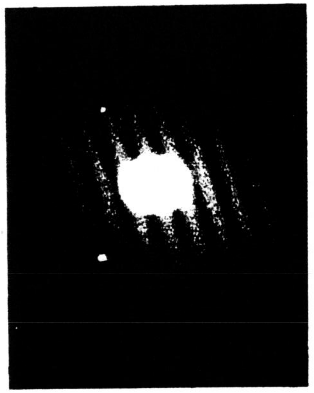

Fig. 3. Speckle interferogram characterizing the field of displacements in the examined specimen

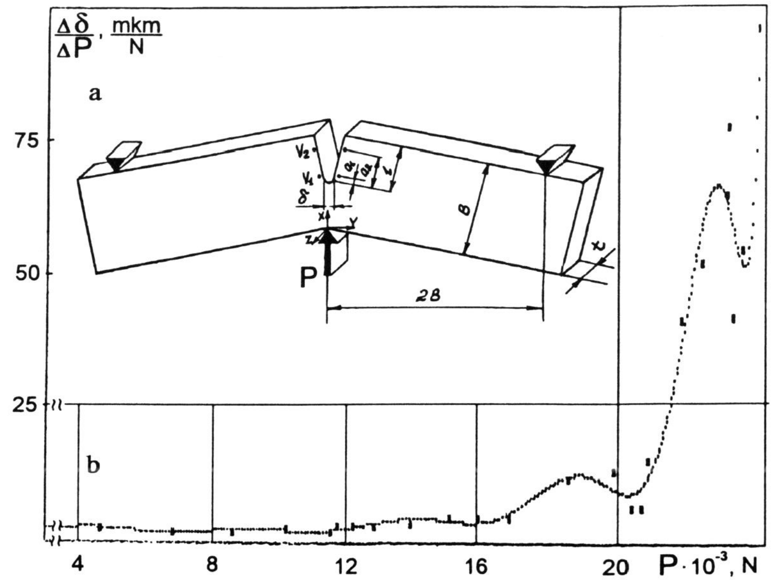

Fig. 4. Experimental study of the crack opening at specimen loading: a - schematic of specimen loading (t =7 mm, l = t, B = $2t$); b - relationship between the crack opening and loading value.

Fig. 4 b presents the results of measuring the crack opening in the described experiment. The diagram reflects the relationship between the increment of value δ and increment of loading P. The analysis of results showed a good correlation between the opening of the tip of the crack-like defect, calculated by the formula and determined with the help of the speckle-interferograms. The difference was not more than 2 %. Besides, the identity of the examined crack-like defects by the mode of deformation and laws of material fracture was revealed.

As a result of the performed experiments it was established that the method of speckle-interferometry is effective in measuring the components u and v of the vector of displacement in the zone around the crack tip. The third component of the vector of displacement (w) is determined by using the method of the holographic interferometry. On the recovered reflecting hologram recorded in opposite beams (by the scheme of Yu.N.Denisyuk [8]) the sequence of the interference fringe N in the examined point was determined. The value of the normal displacement is calculated by the expression:

$$w = \lambda N/2.$$

The carried out experimental studies showed that with the help of the holographic and speckle interferometry methods it is possible to obtain the vector components of displacement in the region of the crack tip, the methods being contactless. The correlation has been established between the mode of deformation and the laws of metal fracture in the tips of a fatigue crack and that with a mechanical saw cut of a radius not less than 0.04 mm.

Thus, by using the methods of the holographic and speckle interferometry all three vector components of displacement are simultaneously measured, corresponding to three main types of deformation in the zone of crack : normal rupture, transverse and longitudinal shears, thus giving new opportunity for the comprehensive experimental study of the processes of the materials fracture under the conditions of complex loading.

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