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HOLOGRAPHIC MEASUREMENT METHODS

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Holographic interference method for studying residual stresses

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***Abstract*. An original procedure is proposed for measuring residual stresses by combining the methods of holographic interferometry and probe holes. The difference of the orders of interference fringes for pairs of points on the surface of a body located on the directions of principal stresses is used as primary information. The results of the test experiment on measuring stresses in a plate deformed in the case of a simple shear and the results of measurement of residual welding stresses in two samples welded by a laser are presented.**

Keywords: *holographic interferometry, interferogram, residual stresses, laser welding.*

Residual stresses appearing during welding and stresses caused by operational loads can produce defects and cracks, resulting in the premature destruction of a construction. Therefore, information on residual stresses is very important for providing the strength and long operating life of constructions. The calculation of residual stresses in welds, especially, multipass welds is a complicated problem, involving not only the development of an adequate mathematical model but also the necessity of using a great body of experimental data (for example, about the mechanical properties of materials at temperatures close to the melting temperature), which are difficult to obtain. Thus, experimental methods play a considerable role in solving such problems [1].

Residual stresses in elements of constructions are usually measured at present by the method of probe holes [1 – 3]. The method is based on the detection of the deformation response of a material to a perturbation produced by a small-diameter hole drilled in the material. The subsequent analysis involves the solution of the inverse problem of solid-state mechanics, namely, the reconstruction of the initial values of residual stresses from measured deformations (displacements).

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The parameters of local strains in the vicinity of a probe hole are measured by using small-base resistance strain gauge rosettes. However, primary information obtained in this way is rather limited and most commonly it only indicates the presence of residual stresses. On the one hand, this circumstance excludes the possibility of static statistic approaches, and on the other, it does not allow one to estimate the adequacy of the real deformation picture to the model used for measuring residual stresses. For this reason, deformations in the vicinity of a probe hole should be measured by the so-called field methods, among which holographic interferometry should be singled out as a contactless highly sensitive method for measuring displacements of points on the surface of a body diffusely reflecting radiation.

The application of holographic interferometry in earlier papers was mainly restricted to measurements of displacement fields normal to the body surface [4, 5]. However, information on the sphere stress tensor was lost, which is undesirable in most cases. Later, a method was proposed for determining residual stresses from the tangential displacement components of points of a body lying directly on the contour of a hole [6]. In the case of a perfectly drilled probe hole, the absolute values of displacements at these points are maximal, i.e. the sensitivity of the method is highest. However, in reality it is the contour of a hole that is subjected to the strongest destructive action during drilling, which can result in practice in the local distortion of the interference pattern, until its disappearance.

In this paper, we consider the method for measuring residual stresses in sheet materials, which is based on the use of primary information in the form of the difference of the orders of holographic interference fringes for two sets of pairs of points selected on the principal strain axes at some distance from the contour of a probe hole. The results of measurements of known elastic stresses in a plate are presented.

Two-exposure reflection holograms were recorded with the help of an optical scheme in counterpropagating beams by illuminating the surface of a body under study by a normally incident collimated beam. A photographic plate is mounted in a special kinematic device, which provides its removal from the interferometer scheme after the first exposure and a subsequent precision return after the drilling of a probe hole [7].

At the first stage of the reconstruction of two-exposure interferograms, the observation vector is oriented along the normal to the object surface, which is taken as the x_3 axis of the laboratory Cartesian coordinate system. In this case, interference fringes are loci of points of equal displacements W from the plane. Because for holes of small diameters ($1-2$ mm), the local strained state can be considered approximately homogeneous, the field of normal relaxation displacements W has two symmetry axes coinciding with the axes of principal residual stresses taken as the x_1 and x_2 coordinate axes. After the visual determination of principal axes, two pairs of interferograms were recorded when the observation vectors were independently oriented in planes x_1x_3 and x_2x_3. Points in the half-space from which observation is performed are usually specified in the spherical coordinate system by the polar radius r, the latitude ψ, and the longitude φ. For $r \to \infty$, observation points are located at infinity, i.e. collimated observation of the region of a probe hole is performed. The centre of this system coincides with the centre of a hole on the surface of a body, reconstructed in the reflection hologram. The direction angles of the observation vector corresponding to the above-mentioned pairs of interferograms are 0, ψ_1 and 180°, ψ_3, and 90°, ψ_2 and 270°, ψ_4, respectively. The optical scheme of a holographic interferometer is shown in Fig. 1. The surface of a body in the region of a probe hole is illuminated by a plane wave in the direction of the unit vector $\boldsymbol{e}_s$.

Each of the points of the surface of an object located on axes x_1 and x_2 is displaced by the values $\boldsymbol{D}(x_1) = [U(x_1), 0, W(x_1)]$ and $\boldsymbol{D}(x_2) = [0, V(x_2), W(x_2)]$ after drilling a probe hole. Let us assume that an arbitrary pair of points lying on the principal x_1 axis and having coordinates (x_{1i}, 0, 0) and (x_{1j}, 0, 0) is observed at an angle ψ_k ($i = 1, ..., I$, $j = 1, ..., J$, $k = 1, ..., K$). By using the main relation of holographic interferometry [8], we obtain two equations

$$U(x_{1i}) \sin\psi_k + W(x_{1i})(1 + \cos\psi_k) = \lambda N(x_{1i}), \tag{1}$$

$$U(x_{1j}) \sin\psi_k + W(x_{1j})(1 + \cos\psi_k) = \lambda N(x_{1j}) \tag{2}$$

for each of the considered points (see Fig. 1), where λ is the wavelength of light; $N(x_{1i})$ and $N(x_{1j})$ are the absolute orders of fringes at points with coordinates $(x_{1i}, 0, 0)$ and $(x_{1j}, 0, 0)$. The directions of displacements are determined by analysing the shape of interference fringes near the contour of a probe hole [9]. By subtracting Eqn (2) from (1), we obtain

$$[U(x_{1i}) - U(x_{1j})] \sin\psi_k + [W(x_{1i}) W(x_{1j})](1 + \cos\psi_k)$$
$$= \lambda[N(x_{1i}) - N(x_{1j})]. \tag{3}$$

Equation (3) can be rewritten as

$$(\Delta U_{1ij}) \sin\psi_k + (\Delta W_{1ij})(1 + \cos\psi_k) = \lambda \Delta N(x_{1ij}), \tag{4}$$

where (ΔU_{1ij}) and (ΔW_{1ij}) are the differences of the displacement components $U(x_1)$ and $W(x_1)$; $\Delta N(x_{1ij})$ is the difference of the absolute orders of fringes at points with coordinates (x_{1i}, 0, 0) and (x_{1j}, 0, 0) equal to the number of interference bands between them.

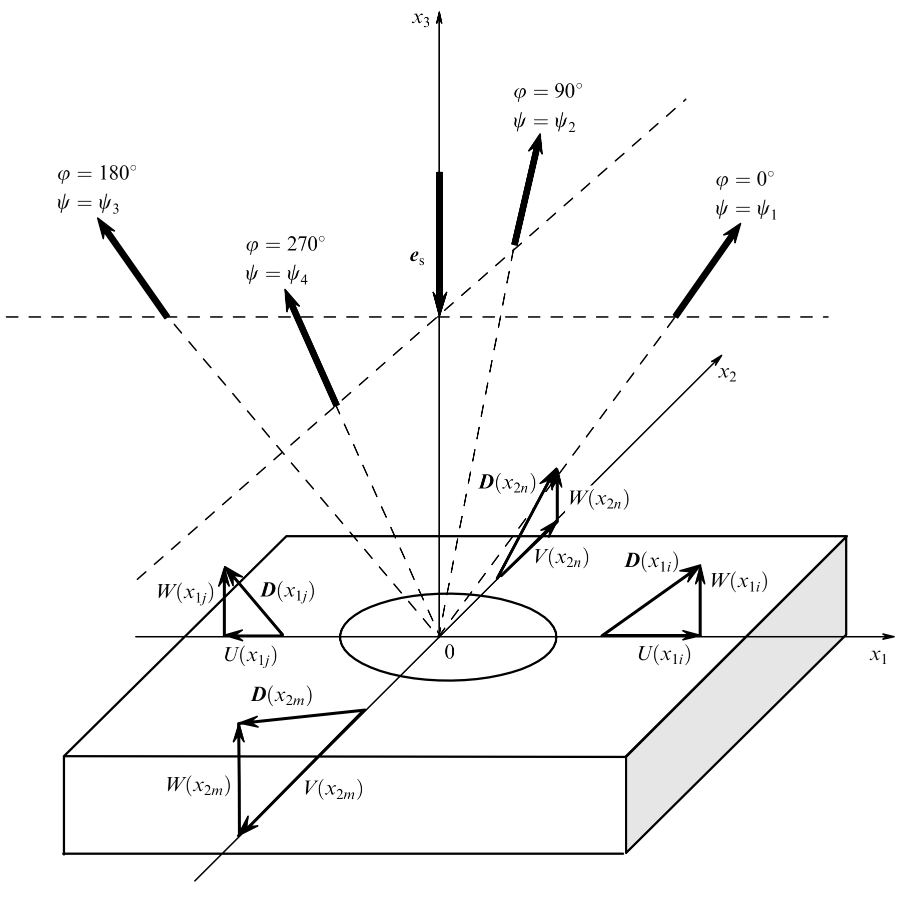

Figure 1. Optical scheme of a holographic interferometer.

The equation for points with coordinates (0, x_{2m}, 0) and (0, x_{2n}, 0) on the principal x_2 axis can be obtained similarly:

$$(\Delta V_{2mn})\sin\psi_l + (\Delta W_{2mn})(1+\cos\psi_l) = \lambda\Delta N(x_{2mn}), \quad (5)$$

where $m = 1, 2, ..., M$; $n = 1, 2, ..., N$; $l = 1, 2, ..., L$.

The functions $U(x_1), W(x_1)$ and $V(x_2), W(x_2)$ are in the general case the sum of local displacements $u(x_1), w(x_1)$ and $v(x_2), w(x_2)$, determined by the deformation in the vicinity of a hole caused by the removal of a material, and of the generalised rigid displacements U^0, V^0, W^0 of the object as a whole with respect to the recording medium (photographic plate):

$$\begin{aligned} &U(x_1) = u(x_1) + U^0, \quad W(x_1) = w(x_1) + W^0, \\ &V(x_2) = v(x_2) + V^0, \quad W(x_2) = w(x_2) + W^0. \end{aligned} \quad (6)$$

The rigid displacements can be decomposed in a sum of the translational and rotational components. It is obvious that translations in the plane of the body surface are mutually cancelled according to Eqns (4) and (5). The translation normal to the body surface affects only the localisation of holographic interference fringes. The contributions from rotations of a body around the axis normal to its surface are also absent because their projections on the coordinate axes are independent of coordinates x_1 and x_2 in the case of small rotation angles.

The remaining small rotations around the axis lying in the plane of the body surface can be written in the form

$$W^0 = Ax_1 + Bx_2, \quad (7)$$

where A and B are unknown constants.

Taking (7) into account, the differences of the displacement components normal to the body surface assume the form

$$\begin{aligned} &\Delta W_{1ij} = \Delta w_{1ij} + A(x_{1i} - x_{1j}), \\ &\Delta W_{2mn} = \Delta w_{2mn} + B(x_{2m} - x_{2n}). \end{aligned} \quad (8)$$

In this connection it is necessary to point out the important circumstance. Rotations of a body around the axis lying in the plane of its surface violate, generally speaking, the central symmetry of the pattern of interference fringes caused by normal displacements. This complicates somewhat the determination of the principal directions of residual stresses. However, the relative contribution of these rotational components of the displacement field in the vicinity of the contour of a probe hole is, as a rule, small, and hence the symmetry of the normal component is retained.

Within the framework of the model of an elastic medium, the distributions of the deformation components of differential displacements for pairs of points along the directions of principal stresses σ_1 and σ_2 can be written in the form

$$\begin{aligned} &\Delta u_{ij} = \sigma_1\Delta F_{ij} + \sigma_2\Delta G_{ij}, \\ &\Delta w_{ij} = \sigma_1\Delta H_{ij} + \sigma_2\Delta Q_{ij} - A\Delta x_{ij}, \\ &\Delta v_{mn} = \sigma_1\Delta G_{mn} + \sigma_2\Delta F_{mn}, \\ &\Delta w_{mn} = \sigma_1\Delta Q_{mn} + \sigma_2\Delta H_{mn} - B\Delta x_{mn}, \end{aligned} \quad (9)$$

where ΔF, ΔG and ΔH, ΔQ are the basis functions of the displacement difference caused by unit stresses acting along axes x_1 and x_2.

For a through hole in a plate, these functions have the analytic form [10, 11]

$$\begin{aligned} &\Delta F_{ij} = \frac{(5+v)R^2}{2E}\left(\frac{1}{x_{1i}} - \frac{1}{x_{1j}}\right) - \frac{(1+v)R^4}{2E}\left(\frac{1}{x_{1i}^3} - \frac{1}{x_{1j}^3}\right), \\ &\Delta G_{ij} = \frac{(v-3)R^2}{2E}\left(\frac{1}{x_{1i}} - \frac{1}{x_{1j}}\right) + \frac{(1+v)R^4}{2E}\left(\frac{1}{x_{1i}^3} - \frac{1}{x_{1j}^3}\right), \\ &\Delta F_{mn} = \frac{(5+v)R^2}{2E}\left(\frac{1}{x_{2m}} - \frac{1}{x_{2n}}\right) - \frac{(1+v)R^4}{2E}\left(\frac{1}{x_{2m}^3} - \frac{1}{x_{2n}^3}\right), \\ &\Delta G_{mn} = \frac{(v-3)R^2}{2E}\left(\frac{1}{x_{2m}} - \frac{1}{x_{2n}}\right) + \frac{(1+v)R^4}{2E}\left(\frac{1}{x_{2m}^3} - \frac{1}{x_{2n}^3}\right), \\ &\Delta H_{ij} = \frac{vtR^2}{E}\left(\frac{1}{x_{1i}^2} - \frac{1}{x_{1j}^2}\right), \quad \Delta Q_{ij} = -\frac{vtR^2}{E}\left(\frac{1}{x_{1i}^2} - \frac{1}{x_{1j}^2}\right), \\ &\Delta H_{mn} = \frac{vtR^2}{E}\left(\frac{1}{x_{2m}^2} - \frac{1}{x_{2n}^2}\right), \quad \Delta Q_{mn} = -\frac{vtR^2}{E}\left(\frac{1}{x_{2m}^2} - \frac{1}{x_{2n}^2}\right), \end{aligned} \quad (10)$$

where E is the elastic modulus of the plate material; v is the Poisson coefficient; R is the hole radius; and t is the plate thickness.

By using expressions (4), (5), and (8)–(10), the system of equations for determining principal residual stresses can be written in the matrix form

$$\boldsymbol{ZS} = \begin{pmatrix} Z_{11} & Z_{12} & \Delta x_1(1+\cos\psi_k) & 0 \\ Z_{21} & Z_{22} & 0 & \Delta x_2(1+\cos\psi_l) \end{pmatrix}\boldsymbol{S} = \lambda\boldsymbol{N}, \quad (11)$$

where

$$\begin{aligned} &Z_{11} = \Delta F_{ij}\sin\psi_k + \Delta H_{ij}(1+\cos\psi_k); \\ &Z_{12} = \Delta G_{ij}\sin\psi_k + \Delta Q_{ij}(1+\cos\psi_k); \\ &Z_{21} = \Delta H_{mn}\sin\psi_l + \Delta F_{mn}(1+\cos\psi_l); \\ &Z_{22} = \Delta G_{mn}\sin\psi_l + \Delta Q_{mn}(1+\cos\psi_l); \end{aligned}$$

$\boldsymbol{S} = (\sigma_1\sigma_2 AB)^{\mathrm{T}}$ is the vector of the required quantities (the superscript T denotes transposition); and $\boldsymbol{N} = (\Delta N_{ij}\Delta N_{mn})^{\mathrm{T}}$ is the vector of the relative orders of fringes. In the general case, the overdetermined system of equations (11) is solved by the method of least squares.

We tested our method for measuring principal residual stresses by using a $70 \times 32 \times 3$-mm plate made of an aluminium alloy and loaded under conditions of a plane stressed simple shear state: $\sigma_{x_1} = -\sigma_{x2} = 70$ MPa [6]. Interferograms were visualised by using the following parameters: $\psi = 50°$, $\varphi = 0, 90°, 180°$, and $270°$. Figures 2a, b present interferograms obtained for $\varphi = 0$ and $90°$. The interpretation of interferograms and solution of the obtained system of equations give $\sigma_{x_1} = 72$ MPa and

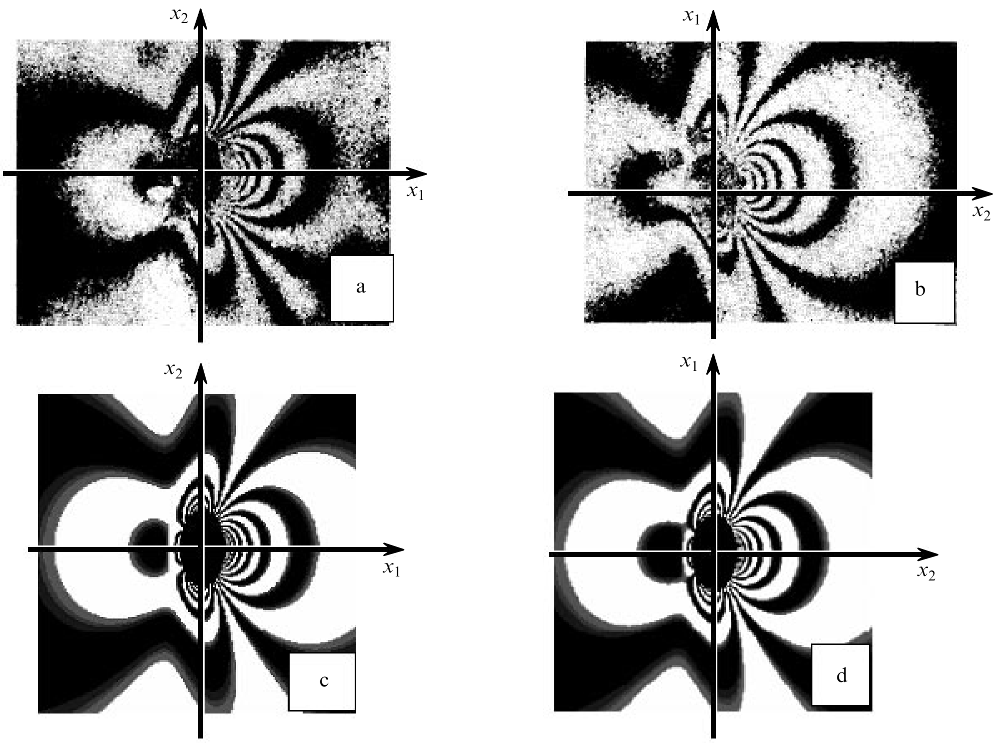

Figure 2. Holographic interferograms of a plate deformed due to the simple shear obtained for $\varphi = 0$ (a) and $\varphi = 90°$ (b) and simulated interference patterns calculated for $\varphi = 0$ (c) and $\varphi = 90°$ (d).

$\sigma_{x_2} = -78$ MPa, which, within an error of ± 15 MPa typical for this measurement method, well agrees with the specified nominal stresses. For comparison, Figures 2c, d show interference patterns simulated by using the above expressions for stresses obtained in the given experiment. The similarity of the corresponding experimental and calculated interference patterns confirms the validity of our physical model for interpretation of experimental data.

It is known that the inhomogeneity of the temperature field and structural transformations caused by welding give rise to residual stresses in the weld and its vicinity. We studied the residual stress fields in the vicinity of the laser weld of aluminium sheets by testing two rectangular samples. Sample 1 was prepared by laser butt-welding of two 2-mm-thick plates; the weld width and thickness was 3 and 2.7 mm, respectively. Sample 2 was obtained by laser welding of two plates of thicknesses 1.2 and 2.0 mm; the weld width and thickness was 1.5 and 2.25 mm, respectively.

Residual stresses at each of the points were calculated by averaging the data for holes of diameters 2 and 2.9 mm. The difference in the measured values of stresses was within the admissible error (± 15 MPa). This means that, within the framework of our model, stresses can be considered homogeneous on the basis of selected diameters of the holes. The calculated dependences of residual stresses on the distance to the middle of the weld are presented in Fig. 3. Curve (*1*) in Fig. 3a corresponds to residual stresses σ_1 in sample 1 directed parallel to the weld, and curve (*2*) corresponds to stresses σ_2 in the perpendicular direction. One can see that the stressed state is close to the uniaxial state. The maximal tensile stress acts along the x_1 axis at a distance of 3 mm from the weld and is 164 MPa. The distributions of residual stresses σ_1 and σ_2 along principal axes x_1 and x_2 are shown in Fig. 3b by curves (*3*) and (*4*), respectively. The most

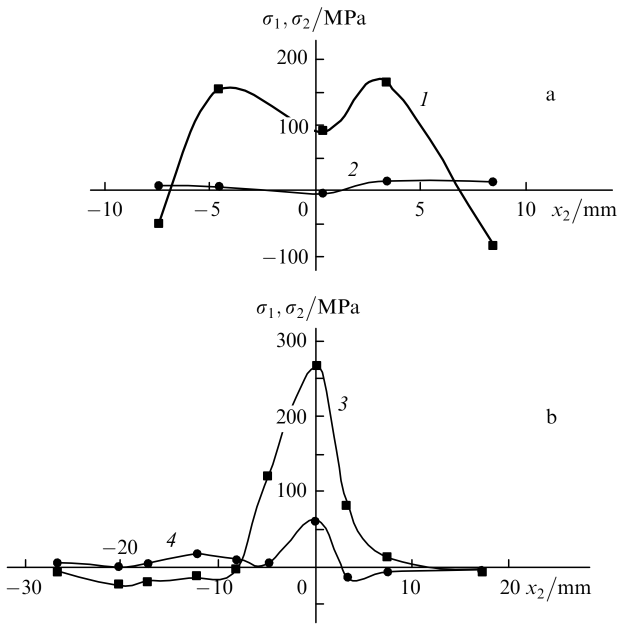

Figure 3. Distributions of residual stresses as functions of the distance to a weld for two samples.

dangerous region from the point of view of strength is the middle of the weld, where the stressed state is biaxial, with tensile stresses $\sigma_1 = 270$ MPa and $\sigma_2 = 62$ MPa.

Thus, the procedure based on the combined use of the methods of holographic interferometry and a probe hole allows the measurement of residual stresses in a weld and its vicinity for laser-welded aluminium samples with an accuracy of ± 15 MPa. The most dangerous region is the middle of the weld where typical tensile stresses σ_1 and σ_2 are 270 and 62 MPa, respectively. The similarity of the experimental and calculated interference patterns demonstrates the validity of the physical model for interpreting experimental data.

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