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STRAIN ANALYSIS OF POLYCRYSTALLINE SPECIMENS BY THE METHOD OF SUPERIMPOSED HOLOGRAPHIC INTERFEROMETRY

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A new experimental method for analysis of the mechanical properties of crystal materials is proposed. The method combines the advantages of holographic interferometry and the contact method of fixing a recording medium. The proposed approach is shown to be effective in determining the surface displacements and strains.

Introduction. The behavior of loaded polycrystalline bodies is modelled numerically in [1–3]. Since numerical modeling of the anisotropy of the physicochemical properties of crystals and the conditions at their boundaries involves some difficulties, it is necessary to develop experimental methods of analysis of displacement fields, in particular, optical methods. The results of application of the speckle-photography method to investigation of the displacement fields on a surface of plane polycrystalline specimens are known [4, 5]. The pointwise scanning method used in these studies to interpret specklograms is labor-consuming and does not allow one to obtain the fields of isolines of constant phase difference on the surface of a specimen. In contrast to the speckle-photographic method, the superimposed holographic interferometry makes it possible to visualize the displacement fields with higher spatial resolution and sensitivity [6].

1. Preparation of Specimens. Specimens of working length 100 mm and cross section 16.2×1.5 mm were milled from commercial aluminum. Then, they were extended on a TsDM-5/91 testing machine, since it has been found experimentally that upon annealing and recrystallization the maximum grain size in a specimen is obtained for a 3% initial strain of the specimen. The elongation of the specimens was measured by a V-630 cathetometer. Annealing was performed for three hours at 630°C in a quartz tube inserted into the working zone of an SUOL muffle furnace. The specimens were cooled for 14 h in the furnace switched off. The specimens were pickled in a strong solution of sodium hydroxide NaOH for 40–60 min. Pickling was terminated if a white film separated independently from the surface of the specimens when they were taken out from a dish.

To determine the grain boundaries on the surface, the specimens were photographed before the experiment for various directions of their illumination (the optical axis of the camera was perpendicular to the specimen surface). Then, the metallized crossed rasters with the line frequency $\psi_x = \psi_y = \psi = 840$ mm^{-1} were deposited on the specimen surface. The arrangement of the grains on one of the specimen surfaces is shown in Fig. 1.

2. Strains in Metal Grains under Static Loading. *Physical Modeling.* The experimental technique is outlined in [6]. Holographic interferograms were recorded at each of 11 stages of specimen loading by a tensile force P. The specimen elongation Δl was monitored by a clock-type indicator whose division was 0.01 mm. The hologram numbers n, the loads P applied to a specimen, and its elongations Δl are listed in Table 1.

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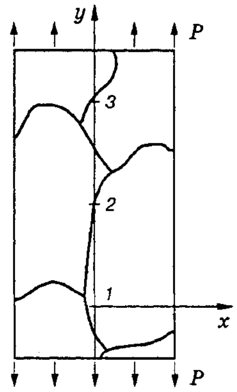

Fig. 1

TABLE 1

n	P, kN	$\Delta l \cdot 10^{-5}$, m
1	0.15	10
2	0.25	17
3	0.35	31
4	0.46	51
5	0.55	93
6	0.59	112
7	0.60	122
8	0.60	134
9	0.60	144
10	0.60	159
11	0.60	178

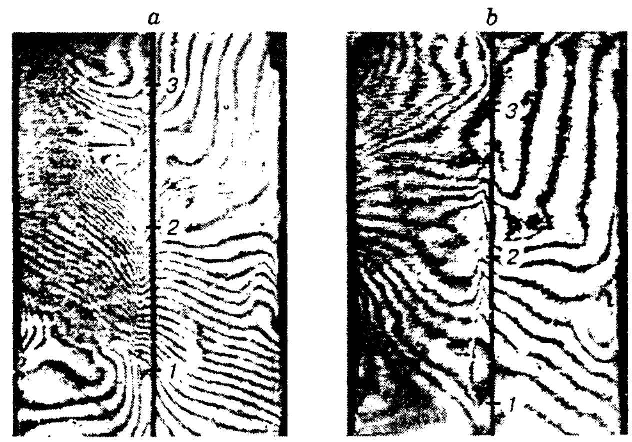

Fig. 2

The photographs of the interferometric patterns observed in the ±1st order of diffraction in reflected light in the yOz plane are shown in Fig. 2a and b for the 6th and 11th stages of loading, respectively. The band patterns were photographed perpendicularly to the specimen surface with the hologram lighted at the angle $\gamma = 32.3°$ in the direction of the first diffraction orders of the raster.

One can distinguish several characteristic zones on the surface of the polycrystalline specimen: the grain regions and the intergrain boundaries [the longitudinal symmetry axis of the specimen almost coincided with the grain boundaries; three boundaries intersect in the neighborhood of points 2 and 1 (see Fig. 1)].

Analysis of the interference patterns shows the following.

1. The deformation of the specimen is quasiuniform at the first two stages of loading.

2. At the third stage, the specimen deforms more intensively in the region of grain boundaries in the lower part of the specimen. However, in view of the small frequency of the interference bands, it is impossible to estimate the degree of nonuniform deformation of the grains and their boundaries.

3. At subsequent stages of loading, the specimen material is deformed nonuniformly. The significant contribution of the shear strains and rigid rotations of the grains is observed in the right half of the specimen relative to the symmetry axis. (One can see from Fig. 2 that the grain in the right upper corner rotates as a rigid body, since the interference-band gradient in this region is almost constant, and the angles of slope of the bands to the x axis are close to 90°.)

4. The character of deformation of separate parts of the specimen changes during loading. At the 11th stage of loading, the entire external load (approximately 0.6 kN) is taken up only by the intergrain boundary in the lower part of the specimen. Without allowance for the scale, the interval between the interference

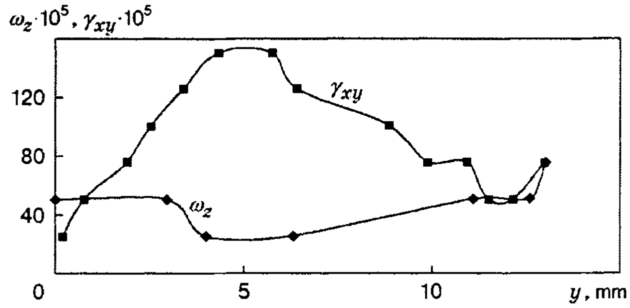

Fig. 3

bands is equal approximately to 0.75 mm; the scale of the photograph is 0.59; therefore, the average strain near the boundary is $\lambda/(2 \cdot 0.75 \cdot 0.59 \cdot \cos\gamma) \approx 0.84 \cdot 10^{-3}$ (λ is the laser radiation wavelength) at this loading stage. If the modulus of elasticity is assumed to be $7.1 \cdot 10^4$ MPa, the average stresses are about 59.8 MPa. At the same time, these stresses are equal to the ratio of a load of 600 N to a part of the area of about 10^{-7} m^2, which is slightly greater than half of the cross-sectional area of the specimen, and amount approximately to 60 MPa.

The interferograms were interpreted quantitatively for the sixth stage of loading. The local parabolic approximation of the band order function $N(x, y)$ was performed with the use of the USMI160 and USMI159 programs [7]. The USMI160 program is developed to approximate the values of $N(x, y)$ at the nodes of a nonuniform grid and to calculate its first derivative. The USMI159 program allows us to obtain a linear combination of the $N(x, y)$ fields for various directions of observation. Since there is an air clearance between the specimen and the photoplate, one can use the following governing equations [8]:

$$\varepsilon_x = \frac{\partial U}{\partial x} = \frac{1}{2\psi}\Big(\frac{\partial N_1}{\partial x} - \frac{\partial N_2}{\partial x}\Big), \qquad \varepsilon_y = \frac{\partial V}{\partial y} = \frac{1}{2\psi}\Big(\frac{\partial N_3}{\partial y} - \frac{\partial N_4}{\partial y}\Big),$$

$$\gamma_{xy} = \frac{1}{2\psi}\Big(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}\Big), \qquad \omega_z = \frac{1}{2\psi}\Big(\frac{\partial U}{\partial y} - \frac{\partial V}{\partial x}\Big).$$

Here ε_x and ε_y are the strains, γ_{xy} are the displacements, ω_z is the rotation, U and V are the displacements along the x and y axes, respectively, and N_1, N_2, N_3, and N_4 are the ordinal numbers of the interference bands recorded in four directions of observation that are pairwise-symmetrical about the z axis.

We use the experimental patterns of the fields of local displacements γ_{xy} and local rotations ω_z to verify the assumption of the wave nature of plastic strain [4, 5]. Figure 3 shows distributions of these components on the longitudinal symmetry axis of the specimen as the specimen total strain increases from 0.58 to 0.70%. The shear-strain distribution within one grain has an extremum near its center.

Mathematical Modeling. The above example shows that much information can be obtained from the interference-band patterns. This makes it possible to use the method of holographic interferometry to clarify whether the mathematical deformation models of polycrystalline specimens adequately fit the experimental data [2].

The quasistatic loading of an element of a structurally nonuniform medium that models the real specimen was studied (see Fig. 1). The initial geometry of the specimen, the boundary conditions (clamped lower boundary), the coordinate system, and the finite-element grid are shown in Fig. 4. Calculations were carried out with the use of the COSMOS/M program for the following physicomechanical characteristics:

— $E_x = E_y = 7 \cdot 10^4$ MPa, $\nu_{xy} = 0.3$, $G_{xy} = 2.7 \cdot 10^4$, $\sigma_y = 300$ MPa, and $E_{\tan} = 515$ MPa for grains;

— $E_x = E_y = 7 \cdot 10^3$ MPa, $\nu_{xy} = 0.4$, $G_{xy} = 2.5 \cdot 10^4$, $\sigma_y = 200$ MPa, and $E_{\tan} = 515$ MPa for intergrain boundaries (dark lines).

The Mises criterion was used as a yield criterion.

To obtain a static solution of the problem, we used the stepwise loading in "time." The "time" parameter is a pseudovariable that determines the sequence of specimen loading. The effect of creep was ignored.

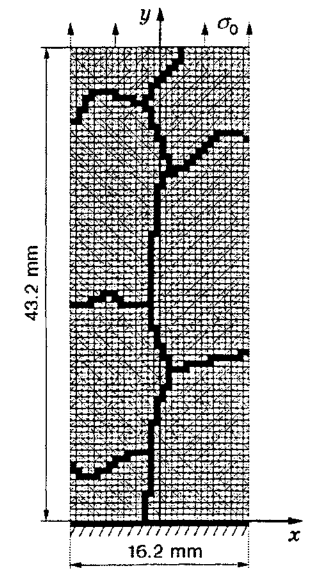

Fig. 4

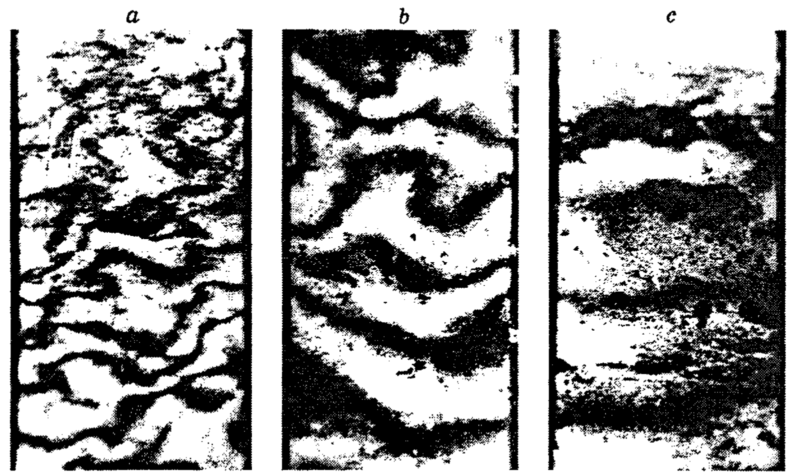

Fig. 5

In accordance with [4], the deformation diagrams for the grains and intergrain boundaries were assumed to be different. The tensile stress σ_0 was specified successively: 40, 80, 120, 160, 200, 240, and 280 MPa. A comparison of the numerical and experimental results shows that the model describes satisfactorily the specimen behavior only at the stage of elastic deformation (the first to fifth stages of loading). Beginning with the sixth stage, the character of the field $V(x, y)$ differs greatly from that observed in the experiment.

3. Strains in Metal Grains upon Reloading. In reloading, the grains are located in the specimen as shown in Fig. 1. During the experiment, the specimen was loaded from 0 to 0.5 kN with the step $\Delta P = 0.05$ kN.

A two-exposure hologram (Fig. 5a) was recorded during loading (the first cycle) in the range of 0.15–0.30 kN. The second interferogram was recorded during unloading (the first cycle) in the range of 0.30–0.15 kN. The resulting band pattern had a regular structure and was identical to that shown in Fig. 5c. The second cycle of loading was performed within 5 min after the first cycle was ended. Two interferograms obtained had a regular system of bands similar to that shown in Fig. 5c. After the two-cycle loading, the specimen was kept unloaded at room temperature for 48 h. Then, the tests were repeated. For loads of 0.15 and 0.30 kN (the third cycle), the interferograms, whose band patterns are shown in Fig. 5b and c, were recorded.

The experiments show the following:

— In the first loading of the specimen, the P–Δl diagram is nonlinear and close to a parabola; the interference pattern has an irregular structure and is similar to the grain pattern; the majority of the bands have breaks;

— In the first unloading of the specimen, the P–Δl diagram is linear; the band pattern has a regular structure and corresponds to the compression pattern;

— After the specimen was kept unloaded for 24–48 h, the first loading pattern was repeated qualitatively, i.e., one can speak of the unhardening effect.

Conclusions. It follows from the experimental data that the results obtained by the finite-element method and the method of holographic interferometry almost coincide in the elastic region. The experimental displacement and strain fields in the elastoplastic region can serve as a basis for subsequent numerical determination of the stresses in a polycrystalline specimen. The superimposed holographic interferometry is sufficiently illustrative to estimate adequately the character of deformation without quantitative interpretation of interferograms.

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