Optical method for determination of fatigue damage in organic glass

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Abstract. The features of nucleation, start, and propagation of a crack inside a transparent organic sample are investigated. The distribution of the refractive index and density around the crack was studied by changing of speckle images and ellipsometry method. It was found that the maximum value of the relative change in density is near the crack. This value before the crack start is greater than 0.003. It is proved that the speckle method we offer can be the basis for the creation of various techniques. Using these techniques will allow us to estimate the time before the crack start by the rate of change of physical quantities in small areas of the order of 50 μm and their limiting values. The results of experimental investigations are presented

1. Introduction
In the modern world, a large number of optical materials are used to solve various tasks [1-9]. Without them of using, it is impossible to conduct the various investigations, especially with using of the laser radiation [10-17]. The optical elements in the exploitation process gradually destroyed by various factors [1-3, 6-9, 18-25]. The fatigue of the material is the dominant factor in the destruction for organic glasses with a large cyclic load [26, 27]. The fatigue of the optical elements disrupts many information processing methods during a taking measurements or research [28-36]. At present, there are not the adequate physical models for the fatigue fracture of organic glasses. For this reason, the simple and reliable methods that unambiguously were interpreting the results of fatigue damage processes investigations inside organic glasses are not developed [1, 3]. The active use of speckle images for the investigations of surface defects in the form of cracks, as well as their application for other tasks [3], allowed us to propose a new technique for detecting and research the expansion of cracks inside glasses.

2. Experimental setup and research method
In Figure 1 shows an experimental setup for studying internal fatigue fracture cracks. The speckle pattern was recorded in the image plane of the sample. To ensure a high degree of contrast when recording speckles, the diameter of the aperture of the lens of the camera 5 was set so that the minimum size of the speckles was slightly larger than the pixel size of the CCD of the camera matrix.

The change in the speckle pattern was determined both visually from the image and using the correlation coefficient η of two digital images of the same size. Digital images were two-dimensional
matrices corresponding to the same part of the frame at the initial moment of time $t_1$ and the current moment of time $t_2$.

![Figure 1. Block diagram of experimental setup for registering a speckle structure: 1-semiconductor laser; 2-polarizer; 3-lens; 4-glass with crack; 5-lens of tv camera; 6-photosensitive elements of tv camera CCD matrix; 7-processing device.](image)

The correlation coefficient $\eta$ is calculated by the formula:

$$
\eta = \frac{\frac{1}{nm} \sum_{i=0}^{n-1} \sum_{j=0}^{m-1} (A_{ij} - \bar{A})(B_{ij} - \bar{B})}{\left(\frac{1}{nm} \sum_{i=0}^{n-1} \sum_{j=0}^{m-1} (A_{ij} - \bar{A})^2\right)^{1/2} \left(\frac{1}{nm} \sum_{i=0}^{n-1} \sum_{j=0}^{m-1} (B_{ij} - \bar{B})^2\right)^{1/2}}
$$

(1)

where $i, j$ are the number of elements (pixels) of the row and the row numbers of the matrix, respectively, $n, m$ are the number of row pixels and the number of rows of the matrix, $A_{ij}$ is the numerical value of the pixel with numbers $i$ and $j$ at $t_1$, $B_{ij}$ is the numerical value of this pixel at the time $t_2$, $\bar{A}$ is the arithmetic mean of the numerical values of the matrix elements at $t_1$, $\bar{B}$ is the arithmetic mean of the numerical values of the matrix elements at time $t_2$.

The correlation coefficient $\eta$ can be displayed on a computer screen every 2-4 seconds (determined using (1)).

3. Result of experimental investigations

In Figure 2 shows the speckle images in the transmitted scattered laser radiation in the presence of a crack inside the organic glass.

![Figure 2. The speckle image from the scattered laser radiation passing through the glass with an internal crack: (a) before the cyclic load, (b) after it.](image)
In Figure 2.b an increase in crack after loading is observed. In the direction of the crack growth, intensified darkening of speckle images is observed. This blackout is less intensely present in Figure 2.a. with a pronounced direction. In case are detected of speckles in reflected scattered laser radiation from a crack, dimming is also present. The contrast of his image will be much less (more than an order of magnitude).

In Figure 3 the dependence of the change in the correlation coefficient $\eta$ on the $y$ coordinate. A laser beam with $\lambda = 632.8$ nm moves along the $0y$ axis along the surface of organic glass. Ambient temperature $T = 294.2$ K.

![Figure 3. The dependence of the correlation coefficient $\eta$ on the $y$ coordinate.](image)

The results showed that for a sufficiently large averaging region (of the order of 0.5 mm), the speckle method allows one to estimate the changes in $n$ near the crack. This made it possible to establish that the maximum relative irreversible changes in density arising from fatigue of Plexiglas are not less than 0.003.

4. Conclusion
The obtained results showed that used the analysis data of speckle images it possible to determine the crack start time with high probability. The method we developed using speckle images in spatial resolution (less than 40 nm) and sensitivity significantly exceeds the traditional coherent-optical measurement and control methods used. This is due to the fact that already in the early stages of fatigue, as a result of the breaking of atomic bonds, disc-shaped defects with diameters of tens of nanometers are formed in organic glass.

The obtained data in during the experiments are extremely useful for creating new methods that allow one to determine the time before the crack start with multi-cycle fatigue of transparent dielectric materials.

Acknowledgments
This research work was supported by the Academic Excellence Project 5-100 proposed by Peter the Great St. Petersburg Polytechnic University.

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