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STOCHASTIC REGULARITIES IN THE NON-CONTACT DETERMIHATION OF LOCAL STRAINS IN THE SURFACE LAYER OF STEEL 45 UNDER HIGH-CYCLE LOADING

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Summary. *The structural material heterogeneity causes the scatter in the mechanical properties. The local stresses in the crystallite can exceed by several times the actual stress values. The order of magnitude of the microplastic strains is 10^{-6} mm/mm, which is below the fatigue limit at normal stresses. Due to the structural and technological factors, the surface elasto-plastic layer of the structural material is less resistant to mechanical damage than the bulk of the material, resulting in a certain number of fatigue failure cases in the total number of failures of metal structures. Non-uniformities in the micro-stress state lead to an irregular development of micro-plastic strains, whose localization affects the evolution of a dissipative structure in a polycrystalline material, which is particularly critical for the subsurface layer. The analysis of the damage state evolution for structure-sensitive parameters of the substructure surface makes it possible to control the mechanical properties of the structural material under high-cycle deformation.*

Keywords: *fatigue, inelasticity, microplastic strains, deformation relief, speckle pattern.*

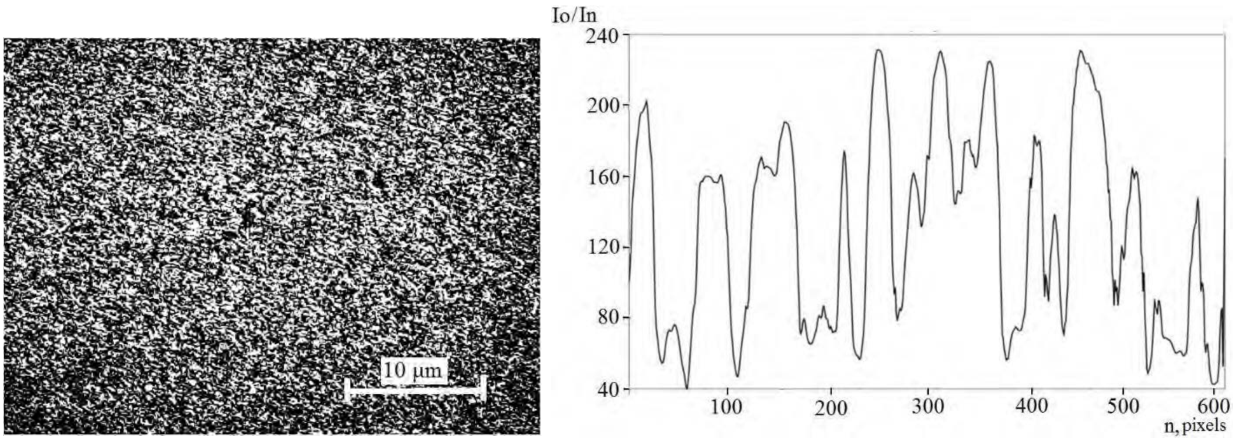
The process of fatigue in structural materials is characterized as exhibiting certain stages, which is caused by the hierarchy of the deformation processes at different scale levels and by their self-organization [1]. The structural transformations are gradually developed, beginning from those at the micro-, meso-, and macro-structural levels, which is due to the self-organization of a dissipative structure, with the most intense development of the deformation processes in the surface layer. In this connection, the methods of quantitative assessment of the structural changes occurring at the surface have a significant place in determining the damage kinetics during fatigue.

Identifying the stages of damage during the high-cycle fatigue is important for monitoring the damage state of a structural material [2]. This is due to that the non-localized damage stage is 90% of the life being larger as compared to the stage of fatigue crack development. Under such conditions, the deformation-induced structural defects are developed in the surface layer to form a stable surface deformation relief. The use of discrete characteristics of optical images of the structural elements at the level of meso- and micro-structural transformations that enable the control of the strain heterogeneity on the surface of a material with high resolution [3-5] can be considered as an efficient modern method for monitoring the damage in terms of the deformation relief irregularity. The relief formation is related to the development of the localized slip plane shears in polycrystalline structure elements. Due to this, a deformation-induced multiple damage is accumulated in an elasto-plastic material. A set of the developed surface shear planes produces a relief whose density is of an irreversible nature. The surface relief has a structure specific to each loading stage. A change in the structure of deformation-induced defects in the surface layer is reflected in the kinetic characteristics of fractal dimension images of the deformed surface.

A non-contact digital image correlation (DIC) method was used to numerically evaluate the microstrain amplitude [6]. The transformation of the Gaussian beam energy transferred from a coherent source of radiation into the reflected speckle-modulated beam energy with a certain ratio of the energies of absorption and reflection by the plastically deformed polycrystalline surface is a manifestation of the combined effect of a dissipative interaction of the metal polycrystal with the deformation energy of the force inducer, which occurs during the strain-induced transformation in the surface layer of the elastic-plastic body. The light beam energy transformation occurs due to the diffusion-mirror reflection of a coherent beam on the scattering centers located in the radiation zone. The scattering regions are the deformation relief elements on the polycrystalline surface of the irradiated object.

The material surface with the deformation relief is irradiated by a coherent beam source with the wavelength commensurate with the expected value of microplastic strains on the metal specimen surface that occur under conditions of loading. In our case, the wavelength of the coherent radiation was 450 nm.

Figure 1 shows a 2D-speckle-structure of the non-deformed specimen surface and the correlation curve of discrete strains in steel 45 based on the measurement scale L= 40 µm



a) b)

Fig. 1 - *a* - speckle-pattern image of the undeformed surface; *b* – correlation curve for discrete strains on the surface

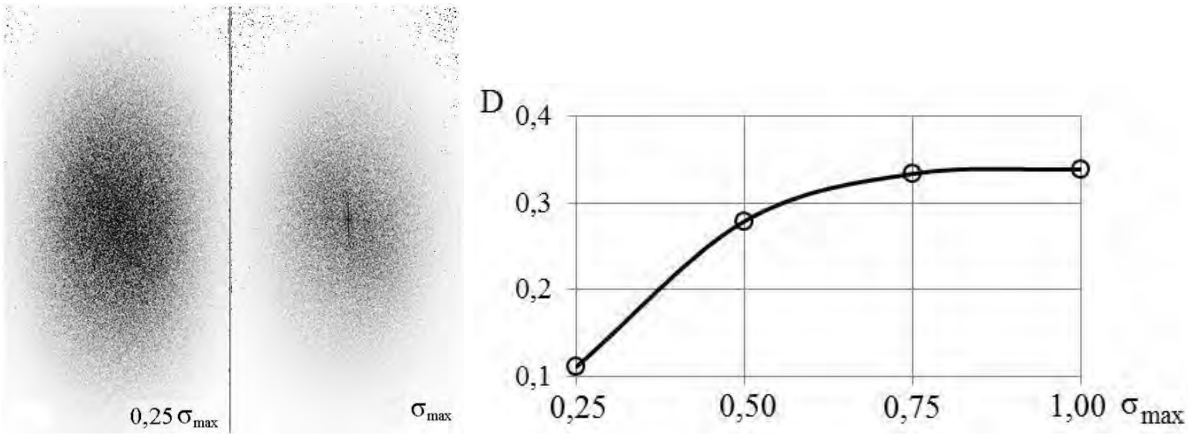
It has been found [7] that with decreasing the gage length for measuring microstrains on the polycrystalline material surface, the resolution required to determine the heterogeneity parameter increases. The dimension of the surface radiation area is (30×40) µm, which corresponds to the scale of microstrain localization on the surface. The resolution of the deformation relief image was 225 pixels per 1 µm^2 of the specimen area.

As the deformation relief is formed, the image brightness level changes monotonically, with the grayscale values ranging from 0 to 255. The binary specklegram mode that enhances the weight of each pixel was used to increase the sensitivity. A decrease in the reflective power of the material surface is represented by the increasing number of dark pixels on the brightness scale pattern. With the growing density of the deformation relief, the reflected beam energy decreases and the diffusely scattered energy increases. As shown in the speckle-pattern image of the surface-reflected beam, the number of pixels increases with the developing deformation relief, which complies with the state of damage depicted in Fig. 2 for the deformation relief of the steel under investigation. The speckle fields were recorded for different stress amplitude values in four cross-sections of the specimen. The specimen, supported as a cantilever, was loaded in cyclic bending with a non-uniform stress distribution along the specimen length. The maximum stresses were in the transition area from the test section to the fillet, whereas at the free edge, the stresses were equal to zero.

The quantity D that is equal to 1 in the maximum damage state was taken as a measure of the deformation relief intensity and defined as a ratio of the number of white pixels to the total number of pixels in the speckle-pattern image. The parameter D characterizes the deformation relief intensity on the material surface.

$$D = \sum n_0 / \sum n ,$$

where n is the total number of pixels, n_0 is the number of white pixels.



a) b)

Fig. 2 - Characterization of the deformation relief on the surface of the steel 45 specimen: *a* – the Fourier spectra of the surface after 10^5 loading cycles at the stress σ_{max} and $0.25\sigma_{max}$; *b* – the kinetic behavior of the histogram for the speckle-pattern image of the deformation relief

The characteristic of fluctuation in the intensity of the histogram for the speckle field fits the growth kinetics of the deformation relief. As the stresses in the specimen cross-sections increase, this characteristic increase, which is in compliance with the intensity of the deformation relief amplitude formation on the surface.

Conclusions.

The correlation characteristic of the deformation relief of steel 45 specimens has been obtained using a coherent radiation with the wavelength λ = 450 nm, which is in compliance with the regularities in the deformation kinetics of the elasto-plastic material under high-cycle fatigue.

It has been found that the employed hardware and software combined system that implements the possibilities of the DIC method to analyze the surface of an elasto-plastic material ensures the resolution in imaging the orthogonal surface strains in the range of 0.5 µm ±10%, which can be used for monitoring the non-localized damage in structural materials under loading conditions below the fatigue limit.

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