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Analysis and automated fatigue damage evaluation of a 17Mn1Si pipeline steel

P.O. Maruschak[1*], I.V. Konovalenko[1], T. Vuherer[2], S.V. Panin[3,4],
F. Berto[4,5], I.M. Danyliuk[1], A. Menou[6]

[1]Ternopil Ivan Pul'uj National Technical University, Ternopil, Ruska 56 str., 46001, Ukraine
E-mail: Maruschak.tu.edu@gmail.com
[2]University of Maribor, Faculty of Mechanical Engineering, Smetanova 17, 2000 Maribor, Slovenia
[3]Institute of Strength Physics and Materials Science SB RAS, Tomsk 634021, Russia
[4]National Research Tomsk Polytechnic University, 30 Lenin Ave, Tomsk 634050, Russia
[5]University of Padova, Stradella S.Nicola 3, 36100 Vicenza, Italy
[6]International Academy of Civil Aviation, Casablanca, Morocco

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Abstract

Digital identification and evaluation of the fatigue damage accumulation kinetics on the surface of the fatigue sensor from steel 17Mn1Si is performed using the digital image processing method. The accumulation of defects was assessed based on the analysis of the diagnostic results for individual stages of cyclic deformation. It is established that the graded nature of the fatigue crack growth is in a good agreement with the parameters of the image of the analyzed surface. Based on the gradual processing of the results obtained for the surface damage the main regularities in the development of shear and rotational processes are found. The theoretical preconditions and experimental results are presented.

Keywords: fatigue, fracture, in-service properties, damage, plastic deformation, stress;

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1. Introduction

The need in ensuring the reliable diagnostics of the technical condition and predicting the residual life of the high-tech equipment is preconditioned by the use of fatigue sensors and development of new algorithms for the analysis of the condition of the surface with fatigue damage Zhou et al. (2002) and Kuang et al. (2008). One of the problems

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solved in the case is an increase in the number of the control parameters of the damage assessment Panin et al. (2014). However, the development of the algorithms for the automated surface analysis, taking into account its structural and mechanical peculiarities, allows increasing the effectiveness of using fatigue sensors Karuskevich et al. (2012).

A number of works dedicated to the approaches of the automated evaluation of the surface condition and design of the fatigue sensors are known Zasimchuk et al. (2012) and Brotzu et al. (2008). In particular, these are the theoretical and experimental approaches, which provide for a more effective realization of the physical principles and methods for the automated processing of the data obtained from the analysis of the deformation surface relief Sutton et al. (1983). The use of the structural and hierarchical approach, which helps establish the graded nature of damage accumulation, is at their heart Elsukova et al. (1996) and Deryugin et al. (1999).

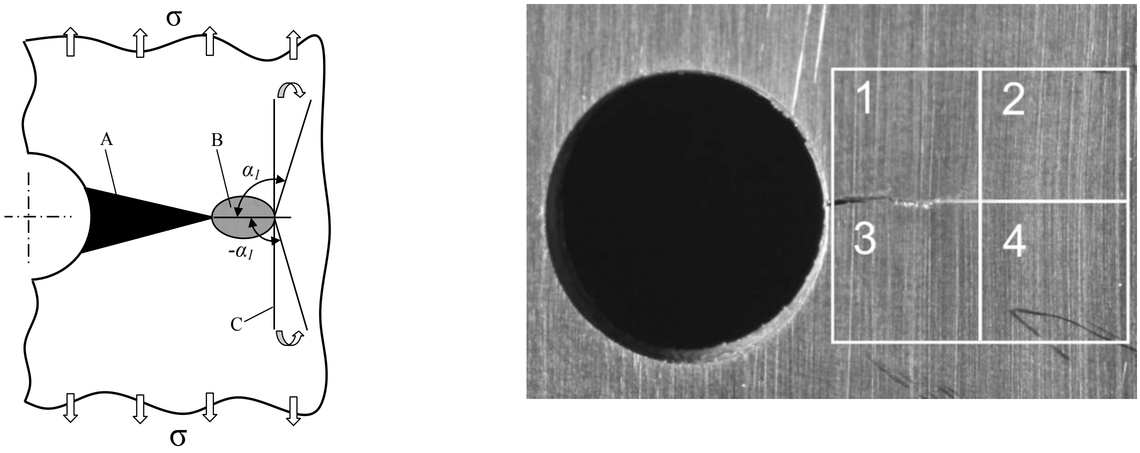
Development of the contemporary diagnostic approaches to the automated analysis, prediction of the deformation behavior and failure of materials after a long-term operation is an important scientific task. Moreover, in order to ensure a correct description of the material behavior, it is necessary to establish a relationship between the local morpho-structural manifestations and physical preconditions of their self-organized formation Panin (2001). It is this that allows evaluating the non-uniformity of the stress-strain state of the system, facilitates the intensification of the technical diagnostics of the condition of the analyzed surface, increases the level of reliability of the analysis. The development of the multi-parameter control approaches, which are based on the correlation links between the detected parameters and formalization, still remains a topical task. An increase in the sensitivity and accuracy of establishing the material condition remains the determining factor in this case Moreno-Navarro et al (2014). However, an increase in the degree of formalization increases specialization of the methods and, correspondingly, limits the area of their application. Therefore, disagreement is possible between the degree of the method formalization and its universality, which should be taken into account and minimized. The purpose of this work is to develop a new method for the automated optical and digital control of the surface damage, and create the mathematical and algorithmic software on their basis. Here introduce the paper, and put a nomenclature if necessary, in a box with the same font size as the rest of the paper. The paragraphs continue from here and are only separated by headings, subheadings, images and formulae. The section headings are arranged by numbers, bold and 10 pt. Here follows further instructions for authors.

2. Research Technique

Flat specimens of size 70 × 10 × 1 mm were cut from the pipe fragment using the electrical discharge method. A central opening of diameter 2.4 mm was cut in specimens before the fatigue tests. They were loaded by cyclic tension within the stress range $\Delta\sigma = 250$ MPa in a Biss UTM-150 servohydraulic installation at a frequency of 10 Hz for the load ratio $R = 0.1$. During the fatigue tests, the surface damage was evaluated using the optical-digital method based on the deformation relief parameters. During the tests, the surface condition was photographed using the Canon EOS 550D camera.

Artificial markers of the shape close to the linear one, Fig. 1a, were applied to the surface of the specimen investigated. In case of deformation caused by cyclic loading and crack growth (A), increased plasticity in the vicinity of its tip (B), markers (C) change their slope. In case of the specimen zones along the crack propagation direction, the slope of markers is different. In order to detect changes in the direction of the artificial surface markers the analyzed area of the specimen was divided into 4 zones (Fig. 1b). Each of the marked zones was analyzed for five points of the optical-digital control.

Moreover, it was presumed that the principle act of plastic yielding is the elementary act of plastic yielding in metals by the scheme “shear + turn” Egorushkin et al (2013). This causes the appearance of the dissipative mesostructures and formation of plastic shears in the vicinity of the concentrator. Failure of the material in the vicinity of the crack tip and crack growth is the final stage of cyclic deformation process at the macrolevel, which consists in the loss of shear stability of mesofragments.



a b

Fig. 1. Scheme for measuring the angle of distortion of markers – (a) and investigated areas of the specimen with artificial surface markers – (b): A – crack; B – plastic zone; C - marker

The processes of deformation behavior of polycrystal (steel 17Mn1Si) under conditions of cyclic loading are investigated. The influence of loading conditions on the local parameters of damage is investigated at the mesolevel, the formation of plastic shears during cyclic plastic deformation is analyzed. During the analysis of each zone of the image the prevailing angles of slope of the artificial surface markers were determined. The algorithm of the image analysis consists of operations that include inversion, binary transformation, and determining the prevailing angle of slope of the detected markers using the Hough transformation.

3. Evaluation of Orientation of Artificial Surface Markers

The initial image for the analysis was the digital grayscale image of the surface $I_0(x,y)$, where *x* is the index of the column, $x=\overline{1,m}$; *y* is the index of the line, $y=\overline{1,n}$; $I_0(x,y)=\overline{0,255}$. In order to detect surface markers in image I_0, segmentation was performed by means of binary transformation. The result was the monochrome image $I_B(x,y)$, in which the brightness of every point was

$$I_B(x,y)=\begin{cases}1, \text{ at } I_0(x,y)>B\\ 0, \text{ at } I_0(x,y)\le B\end{cases} \tag{1}$$

In order to detect the prevailing angle of slope, the Hough transformation, which consists in projection of the image to the parametric space of straight lines, was applied to the obtained monochrome I_B image Duda et al (1972). Let us presume that the multitude of straight lines in the area was given by the parametric equation

$$h(\theta,\rho,x,y)=x\cdot\cos\vartheta+y\cdot\sin\theta-\rho, \tag{2}$$

where (x,y) is the parametric space of the image; (θ,ρ) is the parametric space of the family of straight lines in the image θ,ρ are the components of the normal equation of the straight line).

Figure 2, a-i shows the initial and monochrome images of the artificial surface markers for zone II of the specimen investigated.

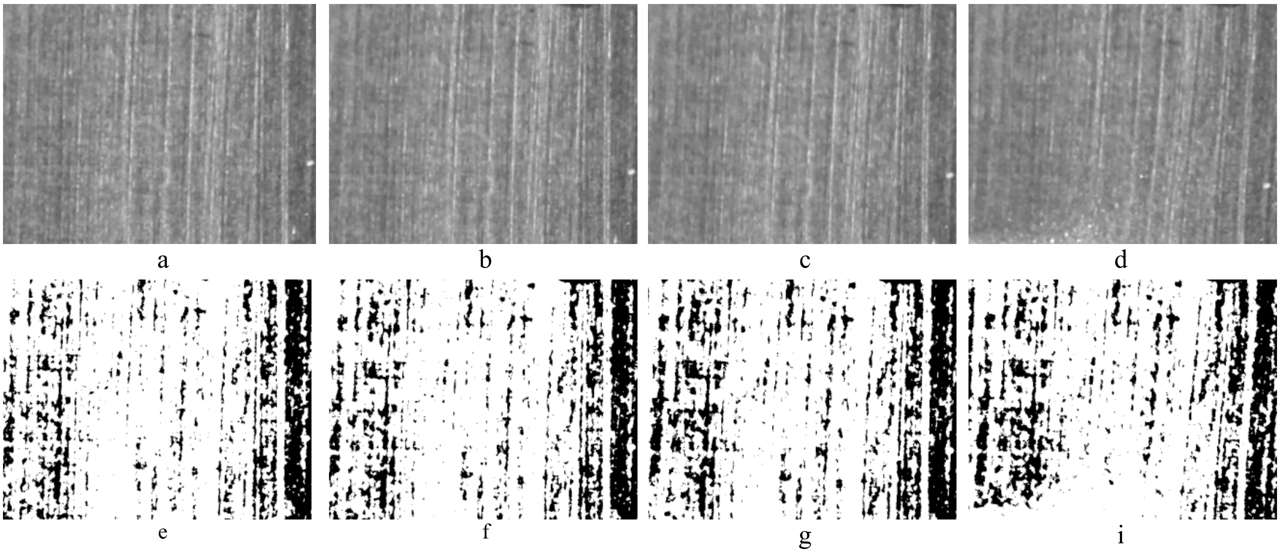


Fig. 2. Digital photos of the surface of zone 2 with artificial surface markers in the points of the optical-digital control (a-d) and their monochrome presentations (e-i)

The matrix of *S* accumulators within the space of parameters (θ,ρ) with discreteness $\Delta\theta$, $\Delta\rho$ (in practice, during the analysis of images it was accepted that $\Delta\theta = 0.5^{\circ}$, $\Delta\rho = 1$ pixel) was calculated in the Hough transformation. The accumulator with a certain number of informative points in the image corresponds to each cell of the phase space. The condition of belonging of point $I_B(x,y)$ in image *I* to straight line *h*, which is given by a cell of the parametric space $S(\theta,\rho)$, was accepted as:

$$r(x,y,\theta,\rho) = \begin{cases} 1, \text{ at } d\left(I_B(x,y), h(\theta,\rho,x,y)\right) <= d_{\lim} \\ 0, \text{ otherwise} \end{cases} , \tag{3}$$

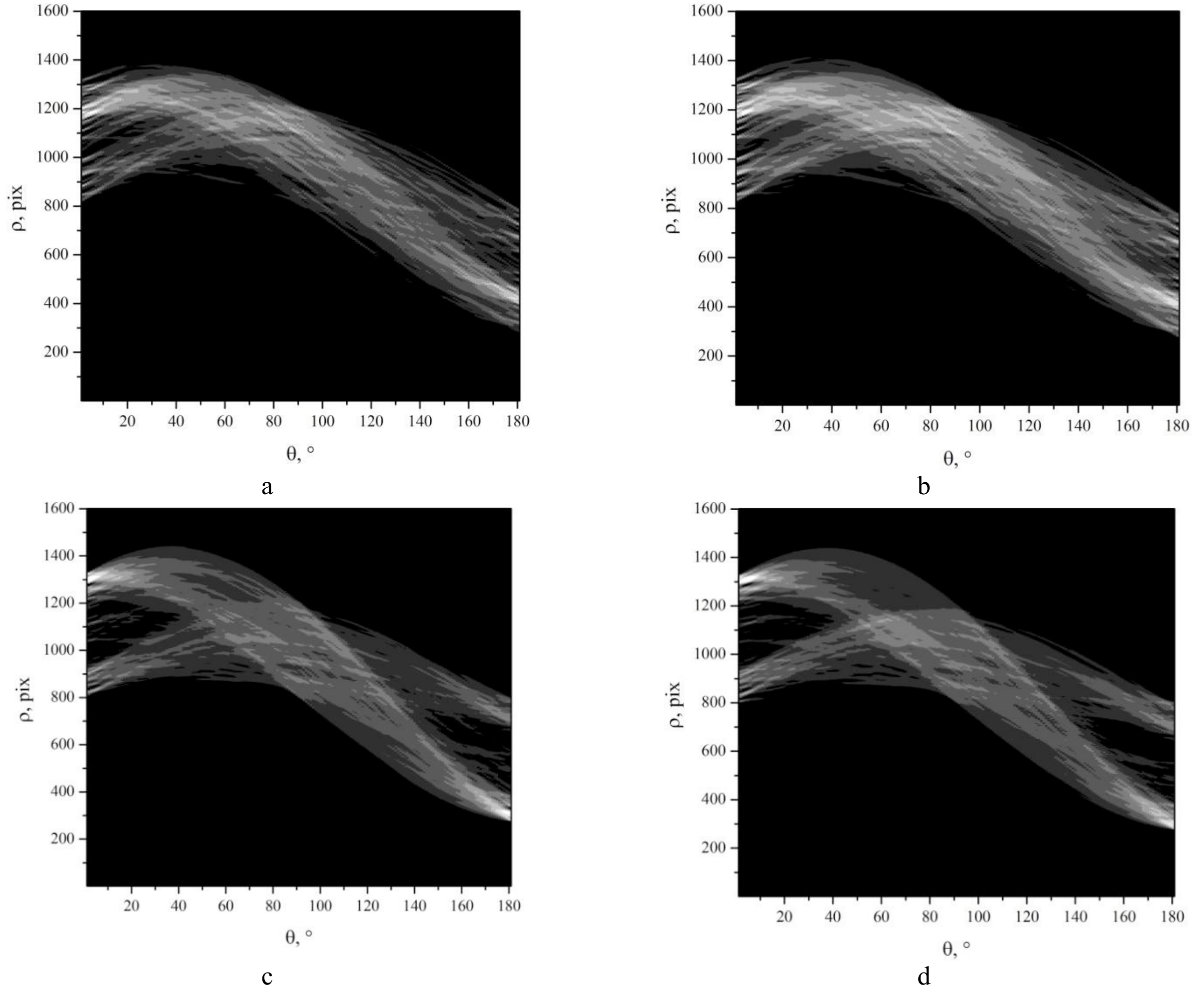
where $d\left(I_B(x,y), h(\theta,\rho,x,y)\right)$ is the distance from point (x,y) to straight line $h(\theta,\rho,x,y)$; $d_{\lim}$ is the limiting value.

Thus, the function of the Hough transformation can be expressed as follows:

$$H\left(S(\theta,\rho)\right) = \sum r(x,y,\theta,\rho) . \tag{4}$$

4. Results of Analysis

The concept of the multilevel description, according to which the translation-rotational shears take place in the material with a crack at the mesolevel, was taken as the physical basis of the method. The quantitative analysis of the accumulators in the parametric space allowed finding straight lines with the greatest number of informative points in the image. The zones, in which function $H\left(S(\theta,\rho)\right)$ attains maxima, correspond to the most pronounced curves. The corresponding value of parameter $\theta = \theta_{base}$ characterizes the prevailing direction of propagation of informative points (elements of deformation relief). The view of function $H\left(S(\theta,\rho)\right)$ for images (Fig. 3, e-i) is shown in Fig. 3, a-d.



a b c d

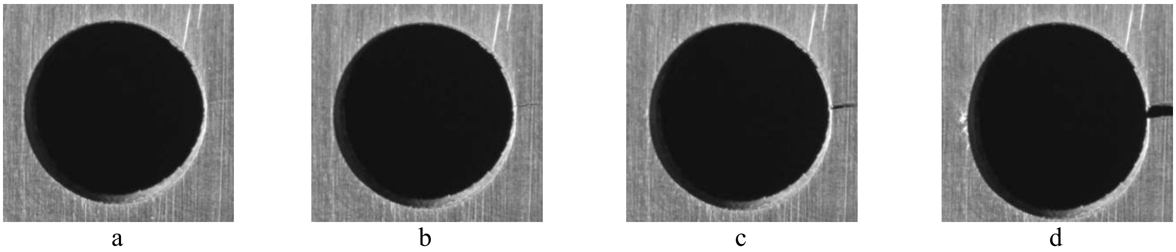
Fig. 3. View of Hough transformation function for images (Fig. 2, e-i)

The zones of the maximum values of function $H\left(S\left(\theta,\rho\right)\right)$ (the lightest zones in Fig. 3) correspond to those combinations of parameters $\left(\theta,\rho\right)$, which form the straight line that passes through the greatest amount of points in the image. The presence of several small peak zones (Fig. 3, a) means that the image contains several well pronounced straight lines. Dilution of the zones of high values of function $H\left(S\left(\theta,\rho\right)\right)$ points to the fact that straight lines in the image are less pronounced. Their displacement along the θ axis testifies to a change in the angle of slope of the straight lines in the image.

The proposed approach allows calculating the influence of the deformation processes on the location and geometrical parameters of the marker lines applied to the surface of the specimen investigated. With an increase in their disorientation, an increase in the Hough transformation function is observed, which testifies to the localized deformation processes in the material. Based on the results obtained it is possible not only to determine the values of damage accumulated in the material but also to assess the nature of their distribution in various control sections over the processing of digital images. Moreover, the ability is provided to perform several measurements in various control sections, in particular, those adjacent to the concentrators and cracks.

5. Technique for evaluation of geometrical parameters of the outlet

With a view to investigating the shape of the outlet its digital images were used (Fig. 4, a-d).



a b c d

Fig. 4. Digital images of the outlet for different points of the optical-digital control over 36135; 38138; 40145; 42152 loading cycles

Binary transformation (1) was applied to the initial images, and the largest solid object found was analyzed. To this end, its area was calculated (the number of pixels that belong to it), and the coordinates of the center of mass. Based on the calculated value of the object area the equivalent diameter d_i of the circle with the same area was calculated. In order to determine a degree of approximation of the outlet shape to the circular one the coefficient of its roundness was calculated Maruschak et al (2014). It accepts values from 1% to 100% and shows how many pixels of the detected object are located in the middle of the circle with the center of mass of the object and equivalent diameter d_i.

6. Discussion

Macromechanisms of the fatigue crack growth are analyzed. The mechanism of nucleation and propagation of the fatigue crack (in section I) has prominent brittle-plastic characteristics, i.e. the crack tip opening is preceded by the development of the translational-rotational vortex deformation of the material, Fig. 5a. In the authors' opinion, the fatigue crack propagates by means of coalescence of microcracks on the boundaries of structural elements.

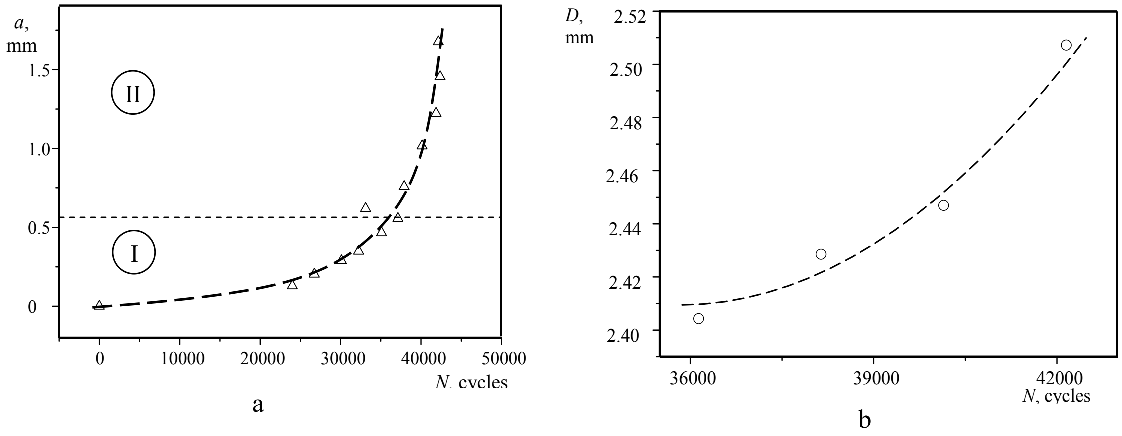


Fig. 5. Dependence of the crack length on the number of loading cycles – (a) and variation of the concentrator shape due to cyclic loading – (b); I – section of nucleation and stable growth of the crack; II – section of pre-critical crack growth

Within the region where growth takes place (section II), a clearly noticeable deformation relief is formed in the form of traces of sliding and shears of surface layers. At this stage of fatigue failure the crack grew by the mechanism of normal separation. Although certain branching of its tip was observed, the nature of displacement of the crack edges testifies to its opening by the said mechanism. A significant stress concentration at the crack tip causes the formation of the couple of the localized strain bands oriented in the direction of the maximum tangential stresses Chan et al (1988). At the pre-failure stage, plastic strains accumulated and actively propagated in the material, a change in the stress-strain state during cyclic loading took place, Fig. 5b. During the analysis of these data the fact that the deformational manifestations are localized mostly in the vicinity of the crack tip was taken into account, Fig. 5b. In addition, a significant physical non-linearity of deformation is noticeable, under which a change in the outlet shape – the concentrator – took place. It is found that the equivalent diameter changes from 2.4 mm for the unloaded specimen to 2.51 mm for the last point of the optical-digital control. The coefficient of roundness decreases from 99.6 % to 97.6 % in this case. The presence of the outlet (stress concentrator), nucleation and growth of the fatigue crack causes the appearance of singularity fields of stress and strain and their further localization, Fig. 5b. It is connected with two aspects – strain concentration at the fatigue crack tip and in the vicinity of the concentrator, moreover, the material does not lose its load-bearing capacity, Fig. 5b. While generalizing the experimental data it was found that plastic materials at the stages of deformation, which precede the appearance of the crack, have localization zones whose optical properties are determined by the field of damage, which has appeared in the material, and the main reason for its appearance is the process of cyclic deformation. The analysis of the regularities in the variation of turning angles of markers in the vicinity of the concentrator during cyclic fracture toughness tests allows stating that they are similar in shape and have a "mirror" view, Fig. 6a, b.

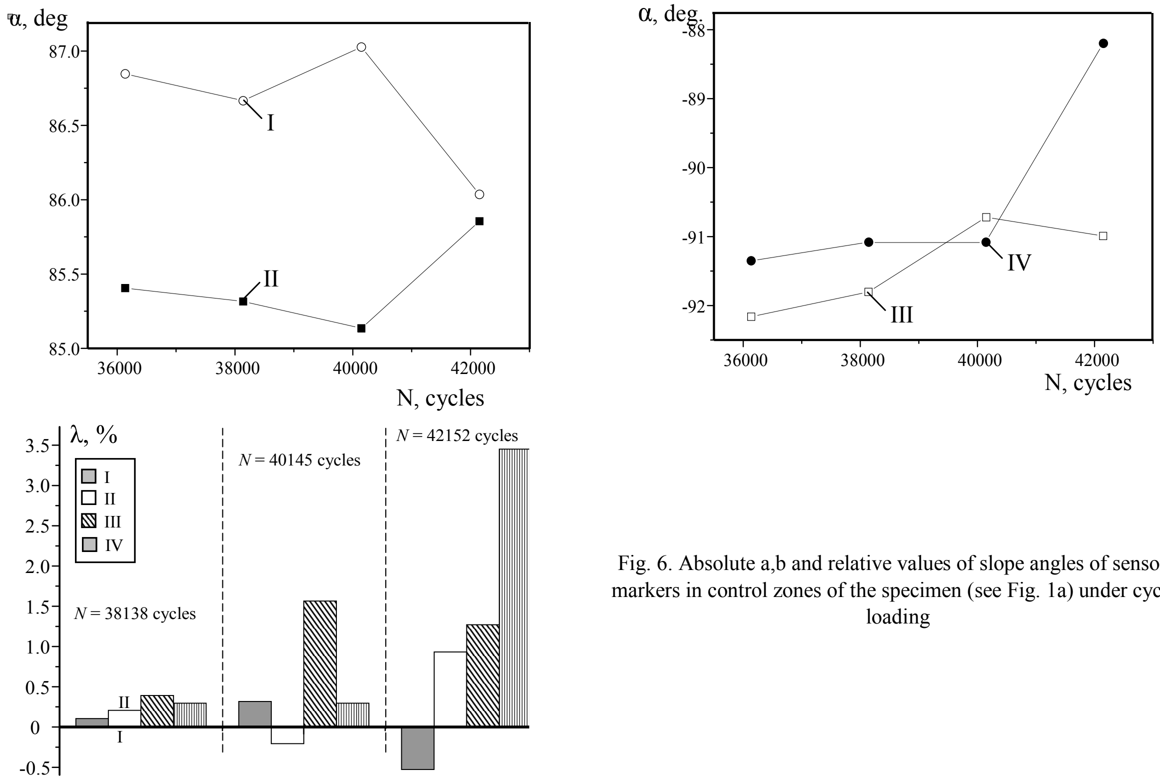


Fig. 6. Absolute a,b and relative values of slope angles of sensory markers in control zones of the specimen (see Fig. 1a) under cyclic loading

This testifies to the fact that the proposed method describes single physical regularities in all the diagnostic zones investigated, which proves once again the appropriateness of using the proposed approach. The obtained diagrams are non-linear and have a slight peak growth in case of 40000 loading cycles, Fig. 6a, b. This peak is preconditioned by localization of shears in bands of plastic yielding and strain gradient along the analyzed surface of the image. Moreover, after this peak the descending branch of diagrams has a gradual increase in the turning angle of the marker in the analyzed zone. The alternation of plastic yielding of various intensity on the curves of linear sections testifies to the gradual accumulation of microdamage in the process of deformation and penetration of the crack, due to which a significant part of stresses on the analyzed section is relaxed, which is depicted in the shape of the diagram. Investigation into the spectrum of markers disorientation during cyclic loading has proven, Fig. 6a, b, that the main factor of variation of the marker orientation is the plastic zone effect, which has appeared at the fatigue crack tip. The spectrum of distortion of markers is preconditioned by the mechanisms of shear and turn of the mesostructural elements (grain conglomerates), and the general variation of the marker orientation was from 0.5 to

4.0%. The obtained results have proven that the data gathered by several bands-markers can be used successfully for determining degradation of the materials investigated, if they are generalized by using the formal damage criterion as the deviation from the initial state – λ, Fig. 6 c. An increase in the marker deviation from its initial orientation together with the crack growth can be seen very clearly for all the specimen zones investigated. Determining the optical-digital control parameters is in a good agreement with the approaches of physical mesomechanics Panin (2001), which allows obtaining the generalizing picture of the deformation and failure process in the material in the vicinity of the concentrator, which meets the limiting, initial and physical conditions and allows obtaining the generalized regularities of deformation and failure of steel 17Mn1Si. One of the advantages is the physical validity of the calculated values of damage obtained on the basis of the data provided by different optical and digital control methods. This has proven a principal possibility of developing the evaluation criteria of the material condition under stress concentration. Another advantage of the proposed approaches is the fact that they allow establishing the relationships between several damage parameters. This approach allows controlling the condition of the main gas pipeline and setting the dates of condition monitored repairs. The calculation of several damage parameters within a single mathematical algorithm ensures the accuracy and reliability of the diagnostic information obtained.

7. Conclusions

The methods of optical-digital control of the condition of steel 17Mn1Si are proposed, which allow calculating several damage parameters. The algorithm of damage identification on the surface of the material with a stress concentrator, which is based on the generalized hierarchical approach, is proposed, the universal mechanism for calculation of the in-service characteristics of the damaged surface is offered. Based on the calculation of the specific variation of the marker orientation, the method for the evaluation of damageability variation in polycrystalline materials is proposed, which is based on determining the degree of the marker distortion in case of interaction with fatigue cracks. The mathematical methods for calculation of the surface deformation, integral evaluation of its condition are developed, which include a description of defects in the form of the formalized hierarchical structure, and allow calculating the values of the detected characteristics. The software, which is a structural model of damage accumulation, was created and implemented, which links the optical-digital properties of the material to the appearance, growth and interaction between multiple deformation defects.

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