Multi-purpose fatigue sensor. Part 2.
Physical backgrounds for damages accumulation and parameters of their assessment

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ABSTRACT. The characteristic informative parameters for defect detection to be used in fatigue sensors have been established. Their development is interpreted in terms of scale levels of deformation and fracture. Damage accumulation of the sensor's surface tends to exhibit the self-organization nature. It is accompanied by formation of "folded" strain-induced relief on the surface. The mechanisms of damage accumulation under cyclic deformation were analyzed with the use of the multiscale approach.

KEYWORDS. Defects; Fatigue sensors; Damage; Aviation.

INTRODUCTION

There is a number of physical backgrounds that explain the nature of an ordered surface relief formation including ones based on the principle of self-ordering [1-3]. One of the most well-known concepts is underlined by the effect of "chessboard" (ordered pattern) of normal compressive/tensile stresses and strains distribution in surface layers and interfaces of solids to occur under the impact of external loading (mechanical, thermal, electrical, etc.). This physical phenomenon is related to the strain incompatibility of two interfaced media and occurs in various multilevel systems: at the "surface layer - bulk material" interfaces, in "coating - substrate" compositions, in multilayered or thin film materials, at grain boundaries (triple joints) in polycrystals [4], etc. It is known that accumulation of defects in surface layers takes place under the cyclic loading that is followed by the material self-organization there that is exhibited in the form of dissipative structure and microextrusions [5-7]. It should be noticed that depending on the mechanical impact on the material the structure of surface damages will be varied. This numerously experimentally proved evidence testifies for the fact that surface layer of the material is the most "sensitive" in order to be used for characterization the kinetics of damage accumulation at various loading modes [8, 9]. These above mentioned properties of material self-organization are widely used at development of instrumental techniques for fatigue fracture diagnostics of aircraft structures [10-12]. A big number of automated methods for monitoring parts made of cladded aluminum alloys are available. In particular, a non-destructive computerized optical-digital inspection technique is based on determination of damage parameter of strain–induced surface relief of fatigue sensors for aircraft structures was described in [13-14]. In doing so the peculiarity of using the strain induced relief as a measure of damage accumulation is related to the fact that the latter is already formed after a few loading cycles and keeps developing till fatigue crack nucleation. This makes possible to run the diagnostic and prediction of the mechanical state and residual life-time of structure elements from the early damaging stage till approaching their limit state. Currently, various parameters which are used for describing strain induced surface relief in structural aluminum cladded alloys being formed under cyclic loading are employed. They typically depend on the nature and accumulation mechanisms of deformation structures at the material surface. Recently, various irregular structures of natural origin are effectively quantitatively described with the use of the following parameters: fractal dimension, Shannon entropy, etc. [7, 10, 12]. In our opinion, the accuracy of the assessment of the critical state approaching in the optical inspection application may be attained by attracting modern techniques of strain induced relief analysis based on calculation of several informative parameters.

The aim of the study is establishing the basic principles of damage accumulation on the fatigue sensor surface under cyclic bending and "bending + torsion" loading schemes.

TECHNIQUES AND MATERIAL FOR FATIGUE SENSOR INVESTIGATION

D16AT aluminum alloy which is widely used in aviation was selected for the research. This alloy has a cladded layer made of pure aluminum for anti-corrosion protection. In doing so, the strain induced relief is formed [7] under the fatigue process. Flat specimens with dimension of $140 \times 10 \times 1.0$ mm were employed for cyclic cantilever bending as well as "bending + torsion" tests. The stress concentrator in the form of a central hole with 1.0 mm diameter was drilled. These allowed us to reveal the basic regularities of strain induced relief evolution under various schemes of the loading. Experiments were conducted with the help of testing machine (home made in the National Aviation University in Kiev) at the stress level of $\sigma_{max} = 107.8$ MPa under the cyclic bending. When complex loading pattern "bending + tension" was used the tensile stress component made $\sigma_{max} = 108$ MPa while the shear one – $\tau = 85$ MPa. The parameters described were constant at the region where surface relief was examined. Surface relief images were captured after certain operating times at the left and at the right from the stress concentrator. In doing so, the optical magnification made $\times 300$. The calculation and comparative analysis of the surface damaging parameters in the regions under observation were performed with the help of automated image analysis.

Algorithm for image analysis

According to data of our recent studies on fatigue sensors behavior the image of regions with accumulated microdefects differ from non-damaged ones by brightness intensity [6, 8]. This is related to the changing sensor surface relief to take place under the loading. The former is responsible for the changing optical properties of the polished surface. In so doing, with the increasing the number of loading cycles, the number and area occupied with plastically deformed surface regions are enlarged [15]. In this response, the following potential informative parameters that might be used for the assessment

of the fatigue sensor state were selected: area of regions being microplastically deformed, as well as the information Shannon entropy. They should indicate the deviation of the surface image of the damaged material from the initial (non-deformed) state (being characterized by low value of the entropy) [16]. To calculate the area of microplastically damaged material the following algorithm was employed. It comprises the following steps: illumination alignment, converting an image into the grayscale one, threshold binarization, computation of the relative area of the "dark" fragments over the total surface region under observation [17]. Since the surface image was registered with the help of the optical microscope equipped with a directed illumination source the "raw" (initial) images were non-uniformly illuminated. This gave rise to the heterogeneity of the background level in various image regions (that affects pattern of microplastically deformed surface). By applying the procedure of the illumination alignment the nonuniformity of the surface illumination was corrected. By converting the image into the grayscale pattern one can substantially reduce the amount of information to be computed as well as to simplify the image processing algorithm. At the next step the aligned illumination image was subjected to the threshold binarization. This operation is aimed at obtaining an image with regions of two types: the light ones (corresponding to the background) and dark ones (corresponding to the damaged regions). The relative area of the damaged regions S_{mda} was calculated as the ratio of dark pixels N_b over the total number of pixels in the image N_t:

$$S_{mda} = \frac{N_b}{N_t} \cdot 100\% \tag{1}$$

The Shannon information entropy was calculated by the formula [6, 8]:

$$H = -\sum_{i=0}^{255} \frac{I_H(i)}{mn} \log_2 \frac{I_H(i)}{mn} \tag{2}$$

where i – pixel brightness, $i = \overline{1,255}$; $I_H(i)$ – image brightness histogram I (the frequency of pixels with brightness); m, n –width and height of the image, measured in pixels, respectively.

The information entropy characterizes the degree of uncertainty in the brightness distribution over the image pixels. It is known that the entropy possesses the maximum value when uniform brightness distribution takes place (i.e., for a rectangular pattern of the image histogram). The entropy of the totally monochrome image has the minimum value.

Since the pixel's brightness of damaged regions and the background are different, the parameter H will depend on the number and size of microplastically deformed regions the image, as well as on their contrast over the background [17].

EXPERIMENTAL RESULTS

It is known that fatigue sensors are strain gauges of integral type which are used in aviation. They are mounted onto bearer carrying structural elements of aircrafts. Since these structures are deattachable they are periodically removed for the aim of automated analysis in the laboratory conditions [8, 12].

Although application of these sensors does not allows gaining information in real-time due to absence of connection to electrical circuits and related communication devices; however their relative simplicity and informativeness makes their use possible not only for aircrafts inspection but for bridge and other building structures as well [7, 8].

Cyclic bending

Optical aided investigations of the D16AT alloy surface after cyclic loading suggest that the latter give rise to nucleation of surface damages, formation of strain induced relief (extrusions, intrusions, sliding traces, etc.). The mechanism of damage formation on the sensor surface is related to the intragranular sliding. In doing so, sliding traces becomes visible within individual grains already after several thousand loading cycles [18]. With the increasing of cyclic loading the larger number of grains are involved into the sliding process, while the formed lines (traces) broaden and unite to form the "spots". These spots are the places of plastic deformation localization. They might be considered as dispersed damages being accumulated within certain grains resulting from relaxation of mechanical microscale stresses [12]. It is the evolution of the strain induced relief during the cyclic loading that allows considering it as an indication for accumulated strain damages. The formation and accumulation of the spots is actively developed especially under long-term operation.
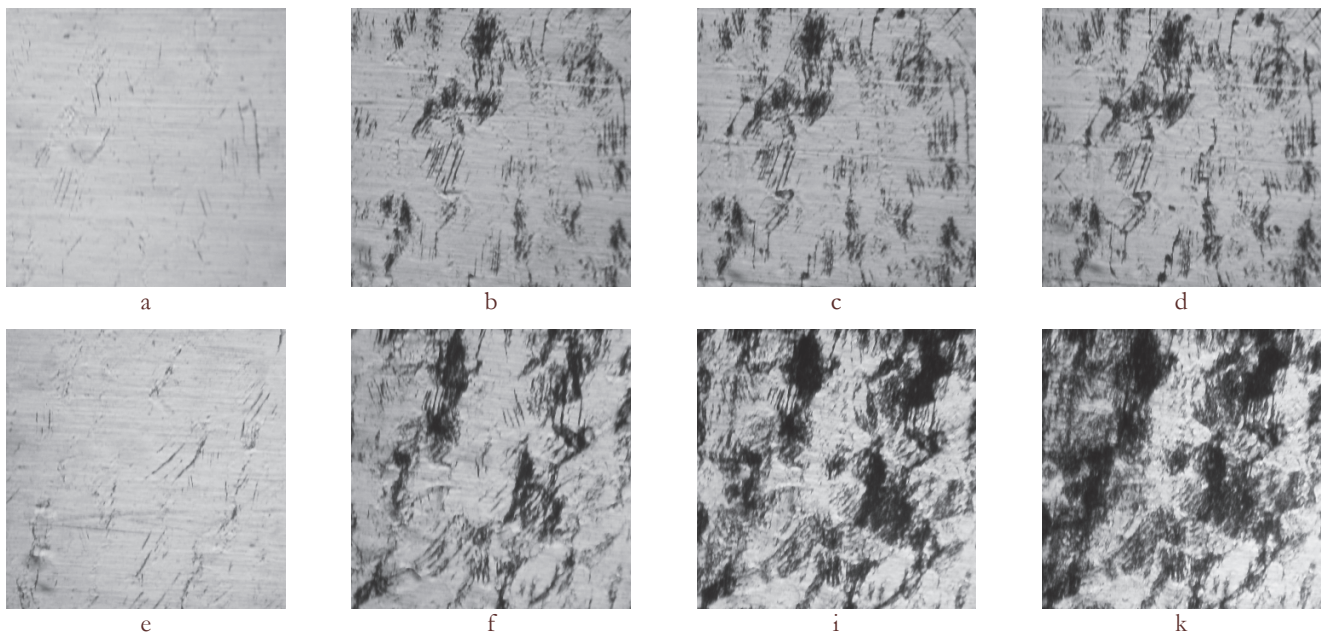
Figure 1: The surface images of strain induced relief found on the structure-sensitive fatigue gauge under bending (a-d) (N = 5000 cyles (a); 150000 (f); 100000 (i); 1000000 (k)), σ_{max} =110 MPa and "bending + torsion" (e-k) loadings: (N = 5000 cyles (a); 25000 (f); 100000 (i); 512000 (k)).

Cyclic "bending + torsion"

Complex loading pattern gives rise to the activation of additional sliding planes in grains that, in turn, increases surface damaging at the same comparable number of loading cycles [19]. In doing so, the multiplicative sliding mechanisms are activated, which, in addition to conventional ones, involve sliding systems, which are not active at uniaxial straining [20]. Three or even more slip planes are additionally involved into the cyclic deformation process when a multiplicative sliding takes place. This results in the reciprocal slippage along adjacent grain boundaries (slipping, translation, rotation). Mutual slippage of adjacent grains provides activation of the surface microrelief formation that, in turn, calls for increase of the damage accumulation intensity. Thus, the kinetics of damage accumulation on the fatigue sensor surface in the D16AT aluminum alloy under investigation at various cyclic loading schemes is different by their physical nature. This specificity should be taken into account when assessing the operating time as well as residual life-time of aircraft components including the use of the digital-optical inspection.

GRAPHS OF CYCLIC DAMAGE ACCUMULATION

Bending

The following data were obtained at the region under inspection located from different sides from the stress concentrator. It was revealed that dependences of damaged area (S) (fig. 2, a) and the Shannon entropy (H) versus the number of loading cycles have nearly the same shape. This testifies for the sensitivity of these parameters to the accumulation of defects within the surface regions under observation, Fig. 2.

"Vertical portion" is formed as a result of intensive accumulation of deformed structures. In doing so, strain develops within individual grains. The tendency of the material to the "easiness" of strain development is determined by the crystallographic orientation of individual grains [21]. The diagram portion responsible for the individual defects being united into the groups is manifested through a gradual increase in the relative area of damaging with signs of microplastic deformation. It gives rise to uniting of the deformation "cluster" and changing of their shape. Dispersed and localized surface damages on the bright surface of the aluminum sensor appear as multiple bands and partially merged spots. - The diagram portion responsible for the uniting of the damages (saturation). Significant reduction of the material resistance to cyclic deformation is characteristic for this part of the curve. Formation and development of "spots" in the regions of their concentration result in the height growth of extrusion and increase of their number [7]. Damage accumulation in D16AT aluminum alloy change in a monotonous manner during running time range is illustrated in fig. 3. This also

proves the possibility of their successful application for the sake of technical diagnostic procedures. The curve to characterize the dependence of the damaged area (S) versus the Shannon entropy (H) exhibit a non-linear character that is related to the difference in their nature as well the background to affect these parameters.
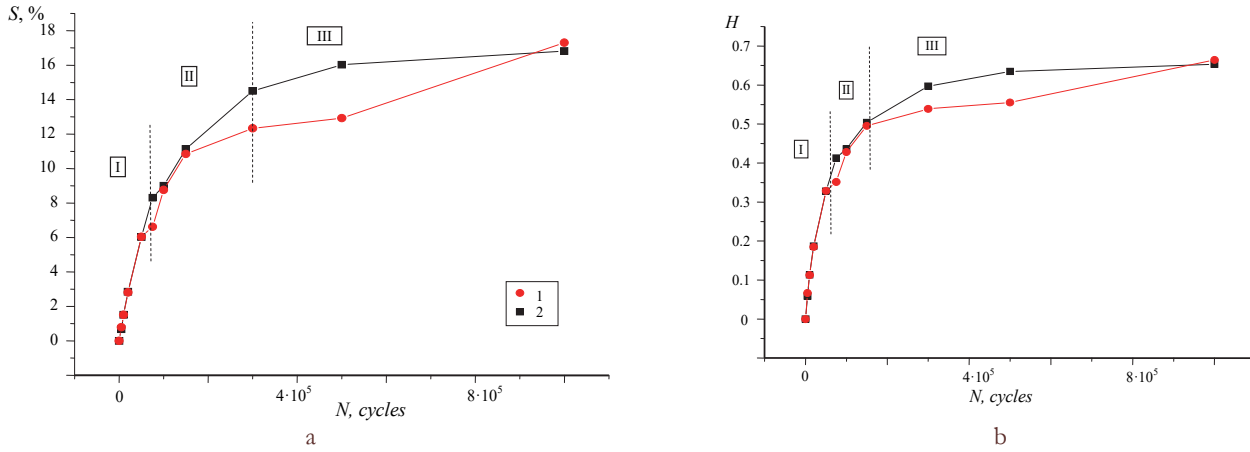

Figure 2: Dependence of the deformed (damaged) area (S) –(a), and the Shannon entropy (H) – (b) vs the number of cycles.
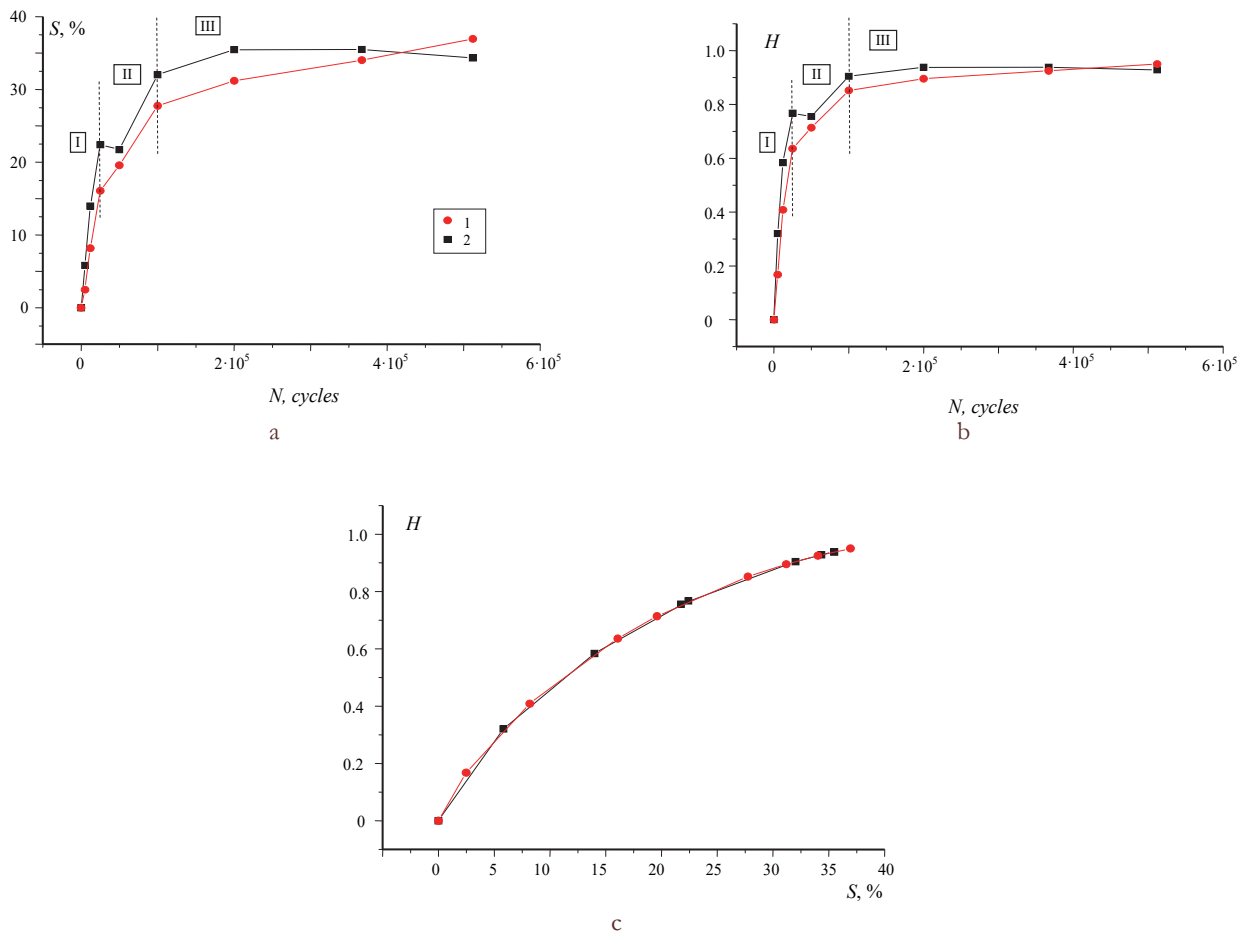

Figure 3: Dependence of the damaged area (S) – (a) and the Shannon entropy (H) – (b) versus the number of cycles and the S – to - H ration under cyclic bending. Images were taken from the right (1) and left (2) sides from the stress concentrator

Bending + torsion

Much like the previous case, the damaging at both sides from the stress concentrator exhibits the 3-stage pattern, Fig. 3. It should be noticed that under "bending + torsion" loading the portion responsible for joining of individual defects into groups is more pronounced as compared to the upper case. The curves to characterize the damaged area and the Shannon entropy are almost identical to ones shown in fig. 2.

By combined analysis of these parameters one can gain deeper understanding on the nature of defect joining as well as prove the self-organization character of processes under investigation. The shape and size of damaged areas testifies for the higher damaging effect of the complex scheme of the loading. However, the stage pattern of damage development on the sensor surface is kept; this allows us to carry out a correct comparative analysis of these curves. Lower degree of nonuniformity of fatigue damaging distribution on the sensor surface during cyclic loading under "bending + torsion" scheme as well as higher intensity of grouping individual defect into larger size conglomerates allows one to determine by a first approximation the loading scheme of a structure at the point of its fixation. The "bending + torsion" loading scheme gave rise to the formation of "concentrated" (localized) black "spots", while the uniaxial loading scheme ensures more uniform distribution of surface defects and the less intensity of damage accumulation. In the case of more complex cyclic deformation the spots had darker appearance and more pronounced shape. It is these parameters that are crucial at formation of the defect domain structure. The attained physical regularities are confirmed by the relative changing of damaging if judging by the both studied parameters:

$$\lambda_H = (H_c - H_b)/H_c \times 100\%,$$

where H_b, H_c – the Shannon entropy values for the bending and "bending + torsion" loading schemes, respectively.

Generalized parameters of specimen's surface damaging being plotted in relative coordinates for different deformation schemes are shown in Fig. 4. The effect of cyclic loading onto the sensor damaging was estimated with the use of a relative factor which allows to analyze the peculiarities of particular combination of the surface damaging parameters (the damaging area of and the Shannon entropy). It is found that at $5 * 10^5$ loading cycles the value of λ_S is reduced from 0.90 down to 0.55, while the value of λ_S drops form 0.80 down to 0.35. This indicates the fact that the difference of sensor surface damaging under the bending and "bending + tension" loading schemes has decreased with increasing cyclic operating time. However the difference in the damaging accumulation kinetics is large enough when judging by the S_{mda} parameter (area of damaged regions). At the same time the value of the Shannon entropy testifies for the faster increasing of localized deformation regions disorientation as compared to the area of the damaged regions.
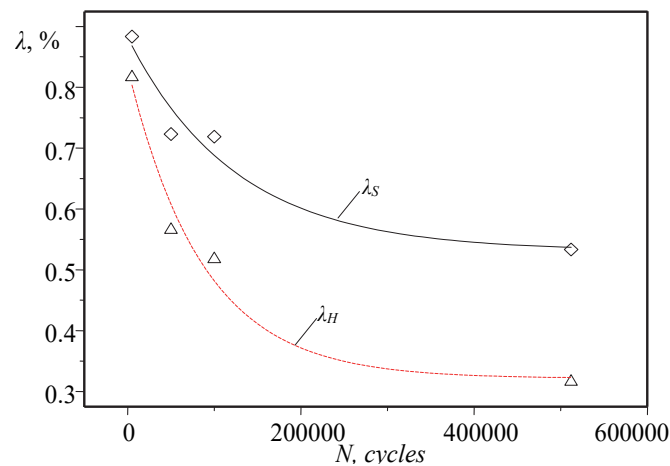

Figure 4: Dependence of the relative damage indicators λ_S and λ_H versus the number loading cycles of the sensor.

Thus, under the "bending + tensile" scheme more active accumulation of the dispersed defects takes place as compared to the "pure bending" scheme. In so doing, they are much more disordered. According to our opinion, the sensitivity of the material (D16AT aluminum alloy) to the loading scheme as well as proper choice of the informative parameters for damaging analysis allows to discuss design of the gauges with controllable sensitive to the amplitude of cyclic straining. The sensitivity of the sensor might be changed by varying their thickness within the region under analysis.

DISCUSSION

Let us analyze the obtained results within the concept of scale levels of deformation and fracture. In contrast with traditional phenomenological interpretation of the results of cyclic damaging of the sensor surface the main characteristic feature of this approach is consideration a solid as a hierarchical system where deformation and fracture processes are self-consistent and develop at the micro-, meso- и macroscale levels [22].

Microscale level. The force affecting the surface layer of the specimen gives rise to changing the stress-strain state of its local volumes, generation, accumulation and annihilation of point defects [23-25]. However, the main relaxation processes are carried due to formation of microscale shear strains. During further cyclic deformation quite damaged surface layer is gradually degraded by accumulating local structural heterogeneities and dispersed damages [24]. The microscale level is characterized by shear processes to develop within the grains experiencing micro-plastic flow, as well as structural changes of the loaded material. Generalization of surface damage mechanisms in the sensor is shown in Tab. 1.

Mesoscale level I. Within the plastically deformed surface layer as well as resulting from mechanical-structural heterogeneity some intrusions occur there which initiate corrugating processes. The latter is accompanied by formation of transverse mesoscale wrinkles to emerge on the material surface. It should be noticed that the described deformation processes do not cover the entire surface, and are concentrated within localized shear bands. With the deformation process development the stress-strain state is changed [25]. This gives rise to the strain redistribution on the surface. As a matter of fact the accumulation processes are terminated in some regions while other ones are activated that is followed by the formation of the relief structures (folds) on the surface.

Mesoscale level II. Stress oscillations occur due to cyclic deformations to develop at the "surface - underlayer" interface that results in additional straining of the surface and subsurface layers [24]. Local deformations substantially exceed the average ones over the specimen which provides activation of sliding processes on the surface and contributes to emergence of additional stress concentrators (in the form of corrugating). In doing so, localized plastically deformed regions are formed.

Macroscale level. The main reason for the nucleation of "spots" on the surface of the fatigue sensor is cyclic deformation and displacement of grain conglomerates. This is proved by the literature data [7, 8, 23] where strain localization and appearance of "spots" on the sensor surface are discussed.

The types of damages and their scale level	The mechanisms of the origin and growth of defects for various schemes of loading	
	bending	bending + torsion
Spots (macroscale level)	Shears and displacements of grain conglomerates in different planes	Shear and rotation deformation mechanisms
shear bands, united in individual spots (mesoscale level II)	Increasing sizes and width of the surface regions covered by extrusions	Uniting of extrusions into "packages", increasing of their height, microscale wrinkling
Mesoscale wrinkles (mesoscale level I)	Formation of predominantly individual extrusion and increasing of their width	Formation of multiple single and adjacent (neighboring) extrusions
Localized shear deformation within individual grains (microscale level)	Formation of shear bands in individual grains	Shears in grains, increasing surface microroughness

Table 1: Scale levels and mechanisms of damage origin.

In a number of previous studied based on the multiscale approach [1] the mathematical modeling techniques to simulate strain induced relief formation at various types of temperature-force impacts on material surface have been developed. The results obtained there make a background for the development of the algorithms for data processing on surface relief formation under cyclic loading [27, 28]. This allows running statistical-based analysis of the surface relief parameters of local spatial regions with taking into account the cyclic, stochastic and localized location pattern of regions with spatial self-organization of surface relief formations. The above described mechanisms are confirmed by the analysis of operating loading conditions of the D16AT aluminum alloy. The analysis of the localization geometry of the strain spots and data on the optical-digital inspection allow concluding on the nonuniformity of the damaged zone development. This is

supported by data [1-3] where the accumulation of damages as a sequence of stages of strain localization is considered. In our case, the activation of additional sliding planes at the complex "bending + torsion" loading scheme increases the formation intensity as well as localization in comparison with the bending loading scheme.
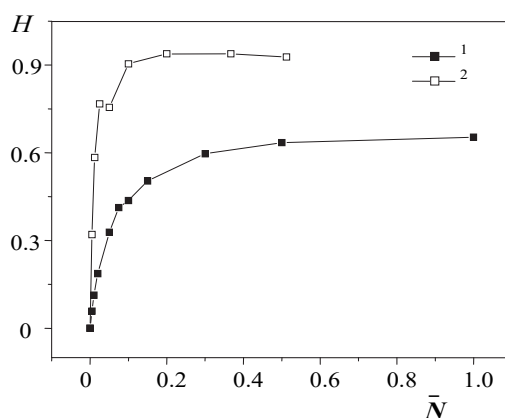

Figure 5: Dependence of the Shannon entropy values versus the relative number of loading cycles of the fatigue sensor: bending (1) and "bending + torsion" (2) loading schemes.

In order to compare the data on sensor damaging at various loading schemes the dependence of the Shannon entropy versus the relative operating time $\overline{N}$ was analyzed. In doing so, a larger cyclic running time (N_c) that is characteristic feature for the bending loading was taken as equal to 1. It is also worth mentioning that the specimens simulating the sensor operation under simple bending have longevity by 1.95 times higher and damaging of 1.42 times lower (at the comparable number of loading cycles). Also, the kinetics of damage accumulation on the surface of the sensor of both types differs mostly in the range of $\overline{N}$ = 0.01-0.1 while after, the contrast in mechanisms of damage accumulation has gradually reduced, Fig. 5.

The above considered issues on the complex analysis of the fatigue sensor damaging at various loading schemes provide an insight into the mechanisms of dispersed damage accumulation and their uniting into the "spots". This is responsible for stage pattern of the process and helped us to justify the application of the proposed approach for the evaluation of residual life of aircraft parts.

CONCLUSION

The basic regularities of damage accumulation in specimen simulating the operation conditions of the fatigue sensors made from D16AT aluminum alloy are revealed. With the use of the automated data processing of digital images to illustrate the damaged surface the curves describing the kinetics of damage accumulation under bending and "bending + torsion" loading schemes were constructed.

Sensitivity of the fatigue sensor surface to the changing of the loading scheme was established during the study at both sides of the stress concentrator. Two parameters – the damaging area and the Shannon entropy were employed to describe the kinetics of damage accumulation.

The dependence curves of each parameter versus the number of operating cycles possess the same shape and stage pattern. It is found that in the aircraft structure these parameters are sensitive to the deformation conditions and peculiarities of dispersed and localized defect accumulation on the surface of the cladded layer of the specimens. The joint use of these parameters was tested and substantiated.

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