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A methodical approach to determining the damage characteristics of cyclically loaded samples of metal structures

Abstract. The article deals with an actual task of developing engineering methods for predicting the durability of modern long-life machines should be based on the methodology for determining the degree of fatigue damage to materials and structural elements. In the development of such a methodology, the work proposes to use modern optical and computer tools that allow analyzing the parameters of the deformed surface of metal structure samples and, on this basis, to estimate the residual resource of the metal structure. The purpose of the article was to substantiate a methodical approach for determining the limit state of damage using photometric analysis of the topography of the micro-deformed surface of cyclically loaded metal structure samples. To analyze the fatigue damage characteristics of metals and alloys, an experimental information system was developed based on the method of coherent optical scanning of the deformed surface of metal structure samples with a resolution of 0.2 μm/px. The obtained specklograms of the photodiode matrix, corresponding to the two-dimensional image of the micro-deformed surface of the sample in shades of gray 0-255, were computer analyzed. This made it possible to construct diagrams of the kinetics of the process of accumulation of the amplitude of the deformation microrelief of the surface of the laboratory samples for the studied steels St 45 and St 20. It is shown that the kinetics of speckle brightness obtained in the work by the correlation method, which corresponds to the evolution of the accumulation of fatigue damage on the surface of the studied structural steel samples, is characterized by a nonlinear function, which is consistent with the results of

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deformation microrelief studies obtained by other methods. The proposed methodology for analyzing the discrete distribution of specklogram brightness can be used to predict the onset of the limit state of a metal structure before failure due to fatigue

Keywords: fatigue of metals and alloys; correlational analysis;, microplastic deformation of the surface; deformation microrelief; photometric scanning

INTRODUCTION

Modern requirements for the operational resource of machines and equipment provide for their long-term operation [1], which can reach 109 cycles based on the declared duration of operation of machines based on cyclic loading. It is also necessary to develop new approaches to create a methodology for tracking fatigue damage of materials and structural elements on large load bases, as a basis for developing scientifically based engineering methods for predicting the durability of modern machines and equipment.

In the calculations of the residual resource of metal structures, the kinetics of scattered fatigue damage accumulation are analyzed depending on the model concept of the material structure. Diffuse fatigue damage develops mainly in the surface layers of the material, so it is important to study the changes in relief amplitudes under the action of cyclic loading [2].

The majority of scientifically based approaches to assessing the degree of damage to metal structures are based on models that use the parameters of the limit sizes of crack-like defects [3], the determination of which is a complicated resource-consuming task in the case of the need to predict the durability of materials and structural elements under multi-cycle fatigue. There is a need to develop alternative methods of research that allow obtaining parameters of the limit state of damage of highly stressed metal structures regardless of the limit characteristics of local centers of destruction. Such approaches include the methodology of determining the parameters of inelastic deformations, the kinetic characteristics of which contain information about the stages of fatigue and the residual resource of metal structures under multi-cycle fatigue in the range of 107-109 cycles [4].

It was shown in [5] that the plastic deformation of a metal from the microyield point to local destruction develops as a result of its dynamic localization at the mesoscopic level. In [6], it was established that in the case of repeated impact periodic loading of metal samples, local destruction occurs as a result of a certain limit accumulation of microplastic deformations in the surface layer. According to the results obtained in work [7], microplastic deformation is realized even under cyclic stresses that are somewhat lower than the endurance limit of the material, determined on the bases of loading recommended by fatigue standards.

This phenomenon is a prerequisite to substantiate the criteria of the limit state of the integrity of the surface of the metal structure based on the amplitude characteristics of microdeformation. The accumulation of inelastic deformations on the surface of the structural material allows the use of optical computer tools for direct measurement of the characteristics of the local deformation of the surface layer of the metal structure [8]. Optical methods, in which remote scanning of the metal structure surface is implemented, are characterized by the appropriate selectivity of detecting defects and their isolation.

Traces of microplastic deformation on the surface of a material cyclically loaded at a stress level close to the endurance limit in the initial stages of the accumulation of fatigue damage can be determined by the methods of atomic force or laser microscopy [9]. The analysis of damage kinetics assessed by such methods is accompanied by methodological difficulties, therefore, in order to assess the accumulated damage on the surface of a metal structure sample in the stages of fatigue before its localization, it is advisable to use correlational statistical characteristics of deformation surface defects. This will lead to a simplification of the method of tracking the transition of the damaged state of the metal structure to the limit with a satisfactory degree of reliability of the forecast under multi-cycle fatigue.

The purpose of the research is to substantiate the methodical approach to determining the characteristics of the physico-mechanical limit state of damage of cyclically loaded samples of metal structures, which precedes the local destruction of the material, evaluated according to the deformation criterion, using photometric analysis of the topography of the deformed surface.

The objectives of the study were to obtain and analyze the regularities of the effect of multicycle deformation on the intensity of changes in the parameters of the microrelief formed on the surface of the steel samples under fatigue.

LITERATURE REVIEW

In the study [10], it was found that the kinetics of propagation of surface and subsurface damage in metal structures depends on the dissipative properties of the material under multicycle loading at the level of 10-4-10-6 relative deformation, which causes the appearance and growth of local microplastic deformations. The achievement of their parameter limit values leads to the local destruction of the metal structure under stresses that do not exceed the elastic limits, i.e. in such places, the destruction is preceded by local microplastic deformation of the metal, as shown in [11].

In [12] it is stated that the limit state of a structural element can be determined by the state of the surface layer formed under external influence, when due to deformation the state of the mesovolume is characterized by a certain parameter of physical and mechanical properties. In multi-cycle fatigue, which is characterized by staged process, diffuse fatigue damage in the form of microscopic cells mainly accumulates in the first stage before the next stage of localized damage formation.

The authors of the work [13] established that the change in physical and mechanical properties under cyclic loading causes the inhomogeneity of local deformation, as a result of which different structural elements of the material are at different stages of damage development, which determines the discreteness of the characteristics of periods of fatigue damage. Likewise, when analyzing the degree of fatigue damage of an elastic-plastic polycrystal, it is necessary to take into account the kinetics of changes in properties during cyclic loading.

The kinetics of microplastic deformations of the polycrystal, initiated by structural mechanisms that depend on the nature of the material, determines the durability of the metal structure. The authors of the work [14] pointed out the importance of studying the structure of surface discrete deformation defects on the metal surface during cyclic deformation. The distribution function of deformation defects reveals the properties of a normal distribution due to the random nature of the localization of shifts in the sliding planes of the polycrystalline structure of the surface of the deformed sample.

It was shown in [15] that slip bands form a deformation microrelief on the surface of a deformed sample as a result of repeated sliding in the crystallographic planes of the surface layer of the material. The amplitude of the deformation relief, which accumulates on the surface of the deformed metal structure sample, corresponds to the degree of structural material damage. The density of deformation defects depends on the parameters of cyclic loading: amplitude and duration of action. Plastic deformation occurs in a limited number of microvolumes, but their number increases with an increase in the number of loading cycles, that is, the specific density of slip bands increases. The parameter of the accumulated damage of structural material samples characterizes the exhaustion of the resource of its plastic properties.

The application of scanning and transmission electron microscopy and methods of quantitative fractography to determine the characteristics of the physical and mechanical limit state of fatigue damage to the surface of structural materials is demonstrated in works [16; 17]. It was shown that the use of these methods allows to investigate certain stages of damage initiation and its development to cracks of critical size, which can be used to estimate the service life of metal structures. In particular, the authors of [18] introduce a certain number of parameters to describe the geometry of the surface microrelief created during cyclic loading, which allows for a more accurate description of the topography of the deformed surface. According to the international standard [19], it is proposed to introduce a system of normative parameters for measuring roughness amplitudes in the case of measuring the characteristics of vertical deviations of the geometric surface of a metal. Taking into account the requirements of this standard provides a summarized determination of the durability indicators of the metal structure according to the criterion of the surface roughness parameter of microplastic deformations.

In published works [8; 20; 21] it is shown that the use of such computerized methods as, respectively, wavelet analysis, fractal parameterization, and the synergistic approach allows to identify patterns of accumulation of fatigue damage on the surface of structural materials and to establish their correlation dependences with fatigue characteristics. In particular, work [22] states that the statistical kinetic characteristics of the accumulation of damage in austenitic steels due to their cyclic loading are correlated with certain parameters of the microstructure, and the revealed correlation depends on the sensitivity of the method used to control the fatigue damage of the material.

So, from the above analysis of publications, it can be concluded that scientists are currently paying significant attention to the issues of assessing the kinetics of fatigue damage accumulation in structural materials, modern computerized methods of measurement and analysis are involved in the study, but research into the possibilities of using engineering methods to control the deformed state of the surface of structural the material is not enough now.

MATERIALS AND METHODS

In this work, the surfaces of flat samples of St 45 and St 20 steels (corset shape, length of the working part – 50 mm, width of the narrowest cross-section of the working part of the sample 10 mm, thickness 3 mm) cyclically loaded on the Amsler testing machine under zero cycles were investigated tension-compression. For the indicated sizes of the samples, fatigue tests were carried out at loading frequencies of about 230 Hz, which made it possible to analyze the kinetics of the formed fatigue microrelief based on cyclic loading up to 5·107 cycles at stresses above and below the endurance limit.

Changes in the microrelief of the surface layer of samples of St 45 and St 20 steels under study were analyzed step by step during the termination of the fatigue tests by the method of evaluating the diffuse scattering of a laser beam reflected from the surface, the brightness of which correlates with the characteristic of the distribution of the spectral density of deformation defects, in particular slip bands [23]. Quantitative assessment of the degree of brightness of the spectrograms, which corresponds to changes in the deformation relief on the surface of the studied samples, was used for calculation and experimental control of changes in the deformed state, which can cause the loss of integrity of the surface of the metal structure due to cyclic loading [24].

The method of atomic force microscopy (AFM) was used to obtain the deformation relief of the surface of the steel sample (Fig. 1).

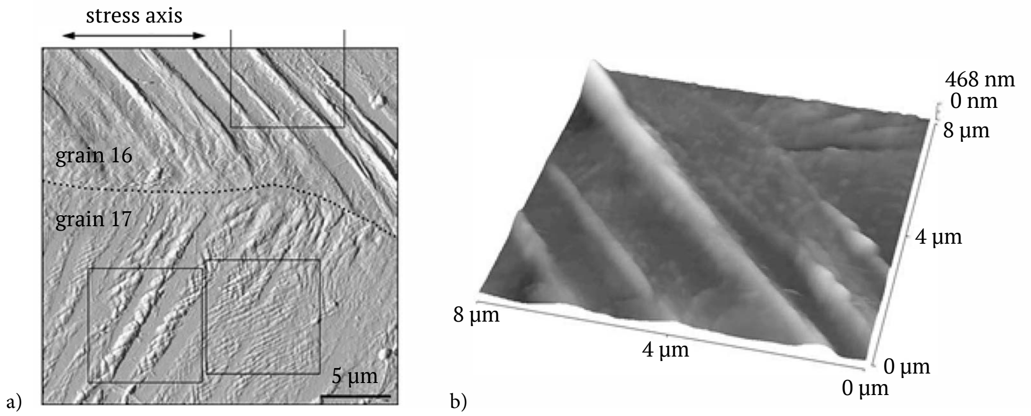

Figure 1. Electronic photograms of the deformation topography of the sample surface:
a – slip bands on the surface; b – AFM image of the relief of microplastic deformations of the surface
Source: [14]

According to the method [25], in this work, the microrelief of developed sliding bands formed on the surface of laboratory steel samples was illuminated by a coherent beam during the intervals of stopping cyclic loading, and in the direction of the beam reflected from the surface, a field of virtual speckles (specklegram) appeared on the LED matrix with discrete brightness distribution. The analysis of the structure of the spectrograms makes it possible to quantitatively assess the degree of accumulation of defects on the surface of the sample. The resolution of the developed experimental information system for the analysis of quantitative characteristics of diffuse damage of elastic-plastic material by the method of coherent optical scanning is up to 0.2 μm/px. [4].

The beam of a coherent light source reflected from a heterogeneously deformed surface contains information about the current state of the physical and mechanical properties of the material surface. The parameters of the two-dimensional image of the surface microrelief with a random distribution of deformation amplitudes characterize the damage of the material, and the brightness parameters of the deformed surface planes of the samples are correlated with discrete deformations, that is, they characterize the deformed state of the surface layer of the material in the case of cyclic loading according to a certain mode [26].

In this work, in order to evaluate the changes in the microplastic deformations of the surface of elastic-plastic materials, which include the studied steels, the metrological characteristics of the angle of reflection of the laser beam were used. Cyclic loading of a certain duration causes a change in the current value of the spatial orientation angle of some local zones of the deformed surface relative to the angle of inclination of the normal vector to the plane of the local surface of the image and the optical axis of the matrix, which leads to a decrease in the intensity of the beam reflected from the surface. The angles of inclination of the surfaces of the deformation relief of the sample, which can be considered as light-reflecting microplates, correlate with the brightness of the virtual speckles of the image on the LED brightness matrix.

The results of determining brightness changes on the photodiode matrix were processed using the PAST program using mathematical statistics methods in accordance with the requirements of the ISO 25178-1:2016 standard [27] regarding the roughness of the engineering surface. In particular, for individual samples of the numerical matrix of luminances corresponding to a certain duration of cyclic loading, the average value of n measurements, dispersion, kurtosis and other statistical characteristics of the sample were calculated. The results of determining the statistical characteristics of changes in the brightness of the deformed surface of the samples made it possible to construct correlational dependences of the degree of cyclic loading of the studied samples with the amplitude of the relief of surface deformation defects.

In order to reduce the dispersion of the analysis results, in the developed photometric method of studying the correlation dependence of the brightness of the speckle structure image with the amplitude spectrum of the relief of local deformation, the correspondence of the correlation parameter within the correlation sample of the general population of data is taken into account. This condition can be fulfilled by stabilizing the homogeneity parameter of the distribution of deformation amplitudes in the local area of one measurement for each sample located within the correlation zone of the general data set. Taking into account the inherent structural heterogeneity of the studied steels, this condition was implemented by reducing the area of the active zone of scanning by a coherent beam to the same average value of the size of the structural element of the sample surface under investigation.

RESULTS AND DISCUSSION

In Figure 2 presents images of spectrograms of the surface of the C 45 steel sample at individual stages of fatigue loading and diagrams of the brightness distribution functions of these spectrograms, constructed along the imaginary intersections of the numerical matrix of the spectrograms corresponding to the imaginary intersections of the sample surface. From the presented images of brightness spectrograms and the corresponding spectral distributions calculated from the data of the numerical brightness matrix, it can be seen that an increase in the number of load cycles is characterized by a significant decrease in the degree of brightness of the images due to a decrease in the number of extremely bright speckles on the spectrograms. That is, the deformation accumulation of damage to the surface of the sample, estimated in this paper by the correlation method, is characterized by a certain nonlinear function, which is consistent with the results obtained by other methods [28].

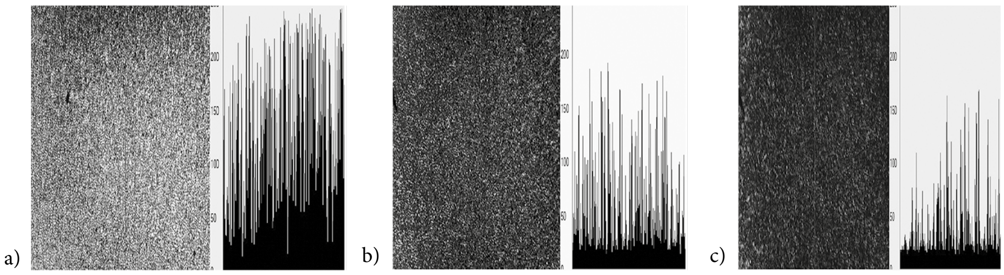

Figure 2. Image of spectrograms and corresponding spectra of speckle brightness in shades of gray 0-255 of the surface of the St 45 steel sample: a – initial state (before cyclic loading); b – the number of loading cycles N=5·105; c – the number of loading cycles N=5·107

Qualitative analysis of spectrograms presented in Figure 2, was clarified by statistical analysis of the numerical matrix of spectrogram brightness in the range of shades of gray 0-255 (Table 1). Presented in the Table 1, the descriptive statistical characteristics of the brightness distribution of the spectrograms at different stages of fatigue are calculated for individual columns of the numerical matrix corresponding to the imaginary cross-sections of the surface of the samples.

Table 1. Statistical characteristics of the brightness distribution of the spectrograms of the micro-deformed surface of the St 45 steel sample under stresses σa=120 MPA (below the endurance limit by 30%)

The number of sample loading cycles N	0	$5 \cdot 10^5$	$1 \cdot 10^6$	$5 \cdot 10^6$	$5 \cdot 10^7$
The maximum value of ***I***	255	200	125	123	140
The average value of ***I***	130.81	116.76	74.52	84.86	89.10
Standard error	7.958	6.065	4.350	5.247	4.501
Sampling variance	3526.26	1365.99	397.46	378.73	425.49
Standard deviation	59.38	36.96	19.94	19.46	20.63
Asymmetry	1.0133	0.6261	0.4065	0.3993	0.3062
Median	113	116	77	90	91
Kurtosis	-0.1992	-0.3548	0.9067	-0.3132	0.4991

Note: *N* is the number of sample loading cycles; *I* – the brightness of speckles in shades of gray
Source: developed by the authors

In the Table 1 shows the generalized results of calculating the statistical characteristics of the number of speckles of the selected gradation of brightness *I* (in the range of shades of gray 0-255), which correspond to the formed microrelief of discrete deformations of the studied surface of St 45 steel samples under different number of loading cycles *N*. The analysis of these data shows that in absolute terms, the kinetics of the degree of brightness of the spectrograms (both with respect to the average and maximum brightness values) is not monotonic in the considered range of loading cycles up to 5·107 cycles. In the case of reaching such a loading base, an increase in the average value of the spectrogram brightness by 5% is observed in the case of an increase in the duration of cyclic loading by almost an order of magnitude, which reflects a certain enlargement of the microrelief of the sample surface at large loading bases close to the endurance limit. At the same time, the effect of cyclic loading was also found for other statistical characteristics of brightness (sharpness and asymmetry of the normal distribution function).

In Figure 3 shows how the shape of the brightness histograms of spectrograms constructed for individual stages of cyclic loading of the sample, specified in Table 1, changes. The value of speckle brightness in shades of gray (0-255) is plotted on the abscissa axis, and the number of speckles n of the sample is plotted on the ordinate axis. From Figure 3 shows how the sharp peaks of the histograms increase, i.e. the number of brightly luminous speckles decreases. Therefore, the sequence of 1 2 3 brightness histograms corresponds to an increase in the specific area of the accumulated deformation of the metal of the surface layer of the sample.

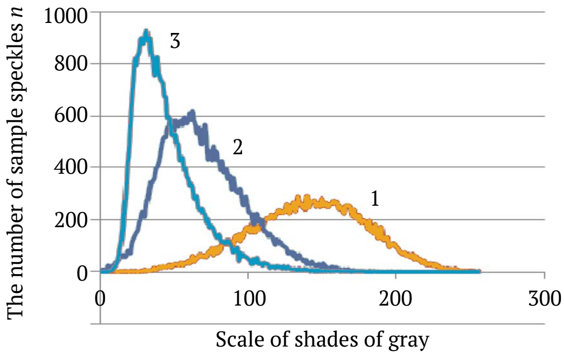

Figure 3. Histograms of the brightness of the spectrograms of the micro-deformed surface of the St 45 steel sample at different stages of cyclic loading: 1 – initial state; 2 – 5·105 cycles; 3 – 5·107 cycles
Source: developed by the authors

Therefore, in order to identify the trends of changes in the deformation microrelief parameters of the studied samples during the stages of multi-cycle fatigue, the statistical characteristics of the brightness distribution of spectrograms in the form of histograms are more informative in contrast to the absolute brightness values.

The system of correlation diagrams that characterize the effect of cyclic loading on changes in the brightness of spectrograms, as a manifestation of the accumulation of the amplitude of the deformation microrelief of the surface of the studied St 45 samples, as well as their trend lines, is shown in Figure 4.

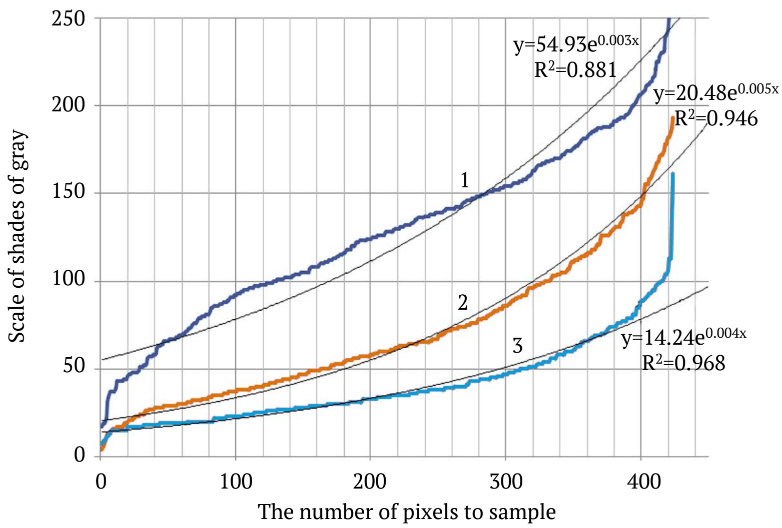

Figure 4. Correlation diagrams of changes in the degree of brightness of spectrograms based on the number of pixels of the sample taken into account, as a manifestation of the accumulation of surface deformations during fatigue of St 45 samples for different stages of cyclic loading: 1 – initial state; 2 – N=5·105; 3 – 5·107 cycles (thin lines depict trend lines with corresponding exponential equations and R2 confidence level)
Source: developed by the authors

Constructed according to the principle of Pareto diagrams, the diagrams in fig. 4 show the monotony of the location with an increase in the duration of cyclic loading and a significant increase in the current state of the instantaneous value of the angle of inclination of the graph in the coordinates of the diagram, as signs of the dynamics of the process of non-localized destruction under multi-cyclic loading. The obtained data are consistent with the results of the study of the accumulation of fatigue damage of metals, which present the stages of the process and a significant increase in damage parameters at the stage before the formation of local macro damage [29; 30]. The peculiarities of the results of the quantitative analysis of the correlation diagrams revealed in this work indicate the expediency of determining the state of fatigue damage of the metal structure according to the criterion of the limit accumulation of the parameter characterizing changes in the brightness of certain (light and dark) elements of spectrograms.

Currently, in the thematic publications on the accumulation of fatigue damage in metallic materials, in particular those mentioned above in this article, insufficient attention is paid to the study of the correlation between the rate of metal damage and the large-scale hierarchy of multi-level damage at the stages of fatigue. The importance of the study of correlation relations under fatigue loading of metal structure samples is indicated in [4], which describes a statistical method for determining the degree of damage under variable loading based on the data of profilometric measurement of the fatigue topography of the sample surface in the range of amplitudes up to 1.0 μm. Based on the calculation and experimental results of the analysis of the morphology of the fracture surface of samples of materials with isotropic and anisotropic mechanical properties, it is proposed to determine a certain constant as a spatial parameter of the surface relief of a solid body characterized by scale invariance. This makes it possible to monitor the general laws of fatigue failure, since the constant relates the parameters of the local and general profile of the surface to the kinetic parameters of fatigue failure. The research results obtained in this work correspond to these principles.

Zones of elastoplastic deformation appear on the surface of the sample under fatigue, which are localized as discrete manifestations of inelastic deformations. The fatigue failure of the metal of the sample is preceded by the accumulation of local macrodisplacements of the surface, that is, local plastic deformation occurs, which leads to local failure [31]. The comparison of microhardness at the fracture sites after monotonic and cyclic loading of the metal showed their close values, which indicates the uniformity of the limit plastic deformations leading to fracture. These deformations are characterized by a diagram of the spectrum of instantaneous values of scattered damage, which relates the topogram of the surface (amplitude of the range of local maxima of the relief) with the duration of cyclic loading. It has been experimentally shown that such a diagram reflects the current state of local strengthening and weakening of metal under cyclic loading [28].

The information presented in Figure 3 and 4, as well as in Table. 1, shows that the correlation method of digital analysis of the surface relief [11] provides experimental and computational means that allow to evaluate critical changes in the deformation microrelief of the samples based on the criterion of the brightness intensity of spectrograms. The digital representation of the brightness spectrum of the spectrogram is correlated with the amplitude spectrum of discrete deformations of the surface microrelief, which create the microrelief of slip bands on the surface of the polycrystalline structure sample. Therefore, the application of coherent optical scanning of the deformed surface of metal structure samples is an effective tool for studying the accumulation of fatigue damage in metal structure samples, as stated in [32].

From Figure 4, it follows that an increase in the duration of cyclic loading leads to a monotonous increase in the amplitude of the deformation relief, which can be represented by linear or exponential dependences, which is consistent with the kinetic dependences of the characteristics of the process of accumulation of microplastic deformation under dynamic loading of elastic-plastic structural materials [23], as well as during the previous cyclic loading of material samples [33], obtained using other methods of metal surface research (acoustic emission).

In order to quantitatively track the state of damage to the surface of structural metal materials, it is proposed to determine the damage (microplasticity) coefficient kD as a correlation characteristic of the deformation properties of the surface of the structural material. This coefficient, which is a quantitative measure of the deformation relief, surface, is calculated according to the formula:

$$k_D=(I_i-I_0)/I_i, \quad (1)$$

where the difference (I_i-I_0) characterizes the degree of damage to the surface area of microplastic deformations in the window area of the base matrix; I_0 – the value of the damage area parameter before loading; I_i is the current value of the damage area parameter. In the case of digital analysis of spectrograms, parameter I should be considered as brightness values of spectrograms in the range of shades of gray (0-255) for the investigated stages of cyclic loading.

In Figure 5 presents the kinetic diagrams of the coefficient of damage of St 45 and St 20 steel samples, constructed based on the results of tests with cyclic stress levels above and below the corresponding endurance limits, which led to different durations of cyclic loading. Testing of St 45 steel samples was carried out under cyclic stresses σa=120 MPa, and St 20 samples under cyclic stresses σa=240 MPa (Fig. 5a) and σa=200 MPa (Fig. 5b).

The presented diagrams can be described by exponential dependencies. From Figure 5b shows that the equations of the diagrams for both studied steels are similar, the slope depends on the magnitude of the cyclic stresses in their considered range, which is consistent with the low intensity of deformation microrelief accumulation on the surface of the samples under stresses close to the endurance limit. In particular, this applies to the laws obtained in [22], which relate the amplitudes of microplastic deformations of the surface of SUS316NG steel samples, determined as a result of direct measurement by atomic force microscopy methods, with the level of loading under low-cycle fatigue.

The results obtained in this work contribute to the creation of scientific and methodological foundations of experimental and calculation methods for determining the residual operational resource of metal structures under the conditions of cyclic loading, as well as methods for tracking the accumulation of deformation defects on the surface of the responsible elements of metal structures under the action of multi-cycle fatigue.

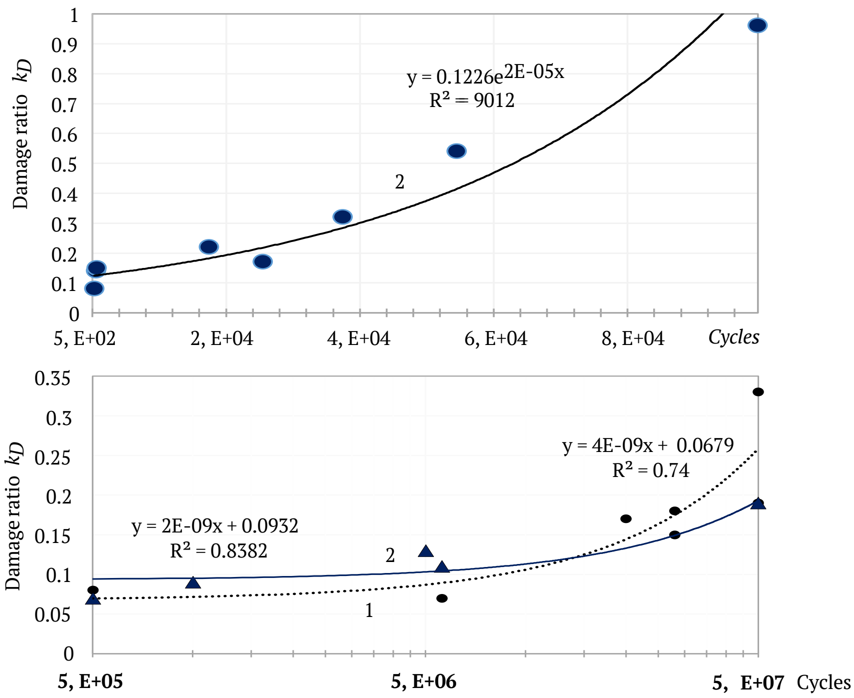

Figure 5. Damage characteristics of St 45 (diagram 1) and St 20 (diagram 2) steels under various cyclic stresses (R^2 – characterizes the degree of reliability of the approximation of experimental data by the equations shown in the figure)
Source: developed by the authors

CONCLUSIONS

An experimental and informational system for analyzing the quantitative characteristics of scattered damage of an elastic-plastic material by the method of coherent optical scanning of a deformed surface with a resolution of 0.2 μm/px has been developed.

The correlation characteristics of the distribution of speckles of the selected gradation of brightness I (in the gray range 0-255) corresponding to the formed microrelief of discrete deformations of the studied surface of St 45 steel samples under different number of loading cycles were calculated. It is shown that in absolute values, the kinetics of the degree of brightness of the spectrograms (both with respect to the average and maximum brightness values) is not monotonic in the considered range of loading cycles up to 5·107. The state of damage to the metal of the sample upon reaching such a loading base corresponds to a change in the average value of the amplitude of the spectrogram brightness by 5.0% due to an increase in the duration of cyclic loading by almost an order of magnitude, which correlates with the state of non-localized damage, determined by a controlled increase in the area of the microrelief of the sample's deformed surface under cyclic stresses close to to the limit of endurance.

The kinetics of the metrological parameters of the geometry of the deformation defects of the surface layer of the sample, formed as a result of cyclic loading at stresses below and above the endurance limit, were evaluated using scanning laser imaging microscopy. The obtained results, which are systematized in the form of correlation characteristics, contain information about the statistical process of microplastic deformation of the surface of St 45 and St 20 structural steels.

It was established that the components of the amplitude spectrum of the microrelief of deformation defects under fatigue, estimated by the parameters of spectrograms, are characterized by the criterion features of the limit state of the surface of the metal structure in the case of cyclic loading under stresses close to the endurance limit. In further research, it is necessary to consider the development of experimental and computational methods that will allow to substantiate the application of the optical-computer method presented in the article for establishing the limit values of the accumulation of fatigue damage on the surface of metal structures that are subjected to long-term cyclic loading during operation.

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Методичний підхід щодо визначення характеристик пошкодження циклічно навантажуваних зразків металоконструкцій

Анотація. В статті розглядається актуальна задача розроблення інженерних методів прогнозування довговічності сучасних машин тривалого ресурсу, яка має базуватися на методології відстеження ступеню втомного пошкодження матеріалів та конструкційних елементів. Мета статті – обґрунтувати методичний підхід для визначення граничного стану пошкодженості із застосуванням фотометричного аналізу топографії мікроздеформованої поверхні циклічно навантажуваних зразків металоконструкції. У роботі було використано розроблену експериментально-інформаційну систему на основі методу когерентно-оптичного сканування деформованої поверхні зразків металоконструкції з виокремівністю 0,2 мкм/пкс. Комп'ютерно проаналізовано отримані спеклограми фотодіодної матриці, що у відтінках сірого 0-255 відповідають двовимірним зображенням мікроздеформованої поверхні зразка для окремих етапів циклічного багатоциклового навантажування. Для досліджуваних конструкційних сталей Ст 45 і Ст 20 виявлено вплив тривалості циклічного навантажування на статистичні характеристики яскравості спеклограм (гостровершинність гістограм та асиметрію функції нормального розподілу). Побудовано діаграми змін ступеню яскравості спеклограм, що відповідають кінетиці накопичування амплітуди деформаційного мікрорельєфу поверхні лабораторних зразків за втоми. Показано, що отримана кореляційним методом кінетика яскравості спеклів, що корелює з еволюцією накопичення втомної пошкоджуваності на поверхні зразків досліджених сталей, характеризується нелінійною функцією, що узгоджується з результатами досліджень деформаційного мікрорельєфу, отриманих іншими методами. Результати дослідження (методологія аналізу дискретного розподілу яскравості спеклограм) можуть бути використані для прогнозування настання граничного стану металоконструкції перед її зруйнуванням внаслідок втоми

Ключові слова: втома металів і сплавів; кореляційний аналіз; мікропластичне деформування поверхні; деформаційний мікрорельєф; фотометричне сканування