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A novel algorithm for damage analysis of fatigue sensor by surface deformation relief parameters

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Abstract

Fatigue damage of metal structures may be estimated by the application of sensors with the surface relief pattern indicating the accumulated fatigue damage. The nature of the deformation relief has been investigated. Digital analysis of the surface patterns based algorithm for the integral evaluation method has proved the efficiency of integral parameters (the general area of damage, mean gradient along the coordinate axes, and the mean amplitude of the histogram function spectrum) application for additional quantitative description of such surface structures. The evolution of deformation relief parameters on the sensors surface is determined by the process of the sensor and construction fatigue damage accumulation.

1. Introduction

It is known that physical mesomechanics considers the surface layers of the material under loading as the independent subsystem highly sensitive to damage accumulation [1]. This was the reason for the development and use of fatigue sensors, which allow obtaining information about the relief, and which are used intensively in military and civil aviation. One of the advantages of such sensors is that they allow getting the physically grounded information, which can be used both during operation and preventive inspections after certain periods of service [2]. Moreover, the acquisition of such information is the basis for the creation of models for predicting the accumulation of damage and nucleation of microdefects.

3D stochastic models of stress and strain distribution on the polycrystal surface are known, which substantiate theoretically the special role of the surface layer in hard bodies under loading, as well as the development of the non-linear undulatory processes in them at the meso- and macrolevels [3]. Such methods allow calculating the distribution of normal and tangential stresses in the surface layers, and on the internal boundaries of the material. The practical value of this consists in the possibility to perform digital modeling of the fatigue sensor condition.

Contemporary profilometry methods allow for the functional diagnostics of the surface condition and recording the morphological parameters of structural formations. However, the

development of the effective approaches to the identification, analysis and generalisation of the obtained data about the surface damage remains topical [4].

The purpose of this work is to develop the algorithm for evaluating the fatigue damage of the foil sensor as the nonlinear hierarchically organised structural-mechanical system, which allows for the calculation of the integral quantitative characteristics based on the analysis of the photo image of the deformation relief.

2. Algorithm for calculation of deformation relief parameters

A foil sensor was fixed on the specimen from alloy D16AT, which was tested under maximum loading of the zero-to-tension stress cycle σ_{max} = 180.0 MPa with the loading frequency of 11.0 Hz [2]. The elementary act of plastic yielding during the accumulation of fatigue damage in the material was the "shear + turn" of structural elements. This caused the appearance of dissipative mesostructures and the accumulation of fatigue damage on fatigue sensors.

The surface relief parameters of the polycrystalline aluminum fatigue sensor were calculated by means of analysis of the initial photo image (Fig.1,a) $I_0(x,y)$. The algorithm consists of two stages. The first stage, the preparatory one, consists of operations that include equalisation of the illumination, filtering, binarisation, and determining the slope angle. During the second stage, the quantitative integral characteristics, which allow evaluating the general condition of the specimen, were calculated by means of analysis of the obtained image.

Preliminary image processing. The image illumination was equalised in order to eliminate the effect of the shaded areas in the initial image on the work result. This operation was performed by folding the image with the low-frequency filter followed by the removal of the low-frequency component.

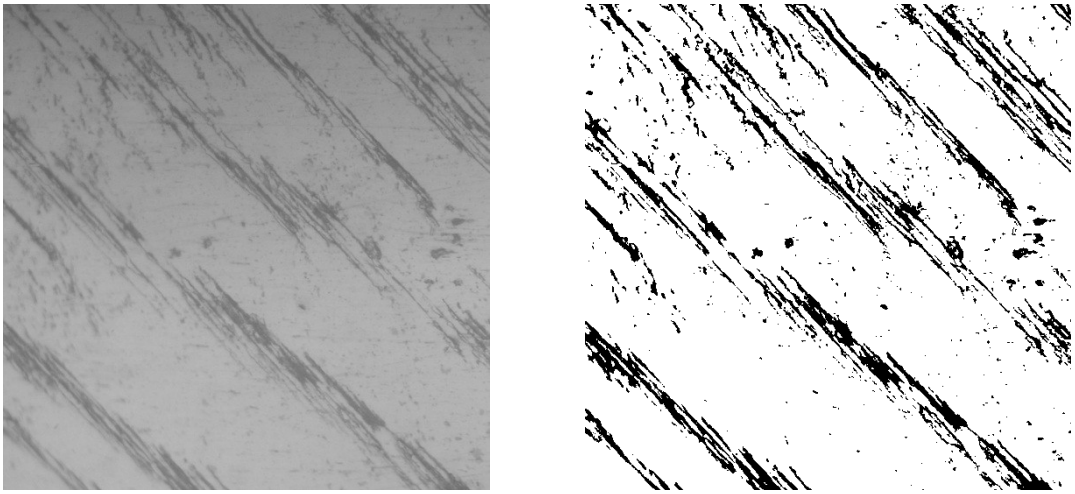
The Gaussian filter with quite a large kernel size was used for filtration, the result of which was the obtained approximate image of illumination $I'(x, y)$ (where x is the column index, $x \in (1...m)$; y is the row index I_0, $y \in (1...n)$).

After that we obtained the image with the equalised illumination:

$$I_L(x, y) = K_L \cdot \frac{I_0(x, y)}{I'(x, y)}, \quad (1)$$

where $K_L = \max(I'(x, y))$ is the illumination equalisation coefficient.

In order to remove minor noise elements from the obtained image, which are caused by the peculiarities of the photomatrix operation, the median filter was used. It was realised with help of the filter, whose window points are sorted in ascending order, and the value in the middle of the ordered list is taken as the initial one. As a result of processing we obtain image I_f.



a) b)

Figure 1: Initial grayscale image (a) and final binary image (b) of the polycrystalline aluminum fatigue sensor surface subjected to 40000 loading cycles

After the preliminary processing and improvement of the initial I_0 image quality the image was segmented. The purpose of segmentation was to distinguish the informative pixels (points of interest) in the image, which correspond to the deformation relief zones. Segmentation was performed using binary transformation. To this end, the limit I_{Blim} value was found in the histogram of the image brightness, which separates the background pixels from the informative pixels.

As a result of the above operations the binary *I* image was obtained (Fig. 1,b), in which black pixels (informative ones) correspond to the deformation relief elements, and white ones – to the background.

The deformation relief on the surface of the polycrystalline aluminum fatigue sensor is characterised by numerous linear fragments (Fig. 1). In order to obtain the quantitative integral indicators of such images [5] it is necessary to have the coordinate system, one axis of which repeats the propagation direction of linear fragments.

Turn of coordinate axis. The propagation direction of linear fragments of the deformation relief was determined using the Hough transformation, which consists in determining the compliance matrix between the image and the parameter space of straight lines (Duda and Hart, 1972). We assume that the family of straight lines in the plane is 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 parameter space of image *I*; (θ, ρ) is the parameter space of the family of straight lines in the image (θ, ρ are the components of the normal equation for the straight line).

In the Hough transformation we calculate the matrix of *S* accumulators in the space of parameters (θ, ρ) with discreteness $\Delta\theta$, $\Delta\rho$ (in practice, during the analysis of images (Fig. 1) it was assumed that $\Delta\theta = 1^{\circ}$, $\Delta\rho = 4$ pixels). An accumulator with a certain number of informative points in the image corresponds to every cell of the phase space. The condition of belonging of point $i(x, y)$ in image *I* to straight line *h*, which is represented by the cell of parameter space $S(\theta, \rho)$, was accepted as follows:

$$r(x,y,\theta,\rho)=\begin{cases}1, \text{if } d(i(x,y),h(\theta,\rho,x,y)) <= d_{\lim}\\ 0, \text{if else}\end{cases}, \quad (3)$$

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

Thus, the Hough transformation function has the following view:

$$H(S(\theta,\rho))=\sum r(x,y,\theta,\rho). \quad (4)$$

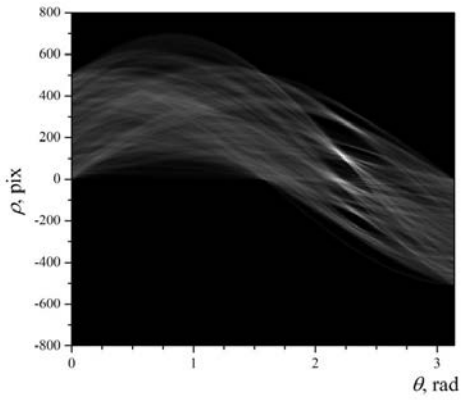


Figure 2: View of function $H(S(\theta,\rho))$ for deformation relief formations

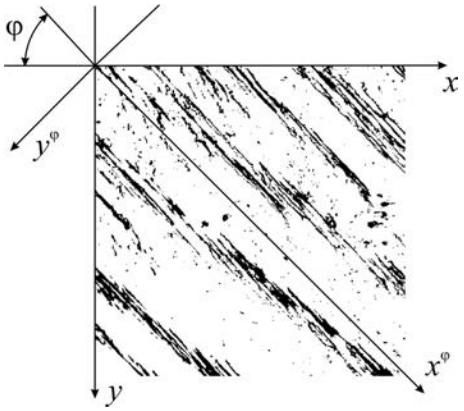


Figure 3: Turn of coordinate system of the image in the propagation direction of deformation relief elements

The quantitative analysis of accumulators in the parameter space allows finding straight lines in the image with the greatest number of informative points. The zones, in which function $H(S(\theta,\rho))$ attains maxima, correspond to the most clearly defined straight lines. The relevant value of parameter $\theta=\theta_{base}$ characterises the predominant direction of propagation of the informative points (deformation relief elements). The view of function $H(S(\theta,\rho))$ for image (Fig. 1,b) is shown in Fig. 2.

Next we consider image *I* in coordinate system $(x^{\varphi}, y^{\varphi})$, which is turned relative to the beginning of coordinate axis (x,y) by angle $\varphi=\theta_{base}-\pi/2$ (Fig. 3). For the image shown in Fig 1,b, angle $\theta_{base}=2.30\,rad=132^{\circ}$.

3. Parameters of quantitative evaluation of relief elements

For the purpose of the quantitative evaluation of the deformation relief condition on the test specimen surface a number of parameters were used, which were calculated based on the analysis of the processed grayscale image I_f and binary image *I*.

For every pixel in image I_f the absolute value of the horizontal and vertical gradient was calculated:

$$\nabla I_f^{\,h}(x^{\varphi}, y^{\varphi}) = \left| \frac{\partial I_f(x^{\varphi}, y^{\varphi})}{\partial x^{\varphi}} \right|, \quad \nabla I_f^{\,v}(x^{\varphi}, y^{\varphi}) = \left| \frac{\partial I_f(x^{\varphi}, y^{\varphi})}{\partial y^{\varphi}} \right|. \tag{5}$$

In order to generalise the evaluation of the investigated surface condition the mean values of the horizontal and vertical gradients of the image were used:

$$G_h = \overline{\nabla I_f^{\,h}} = \frac{1}{S_I} \iint \nabla I_f^{\,h}(x^{\varphi}, y^{\varphi}) dx^{\varphi} dy^{\varphi}, \quad G_v = \overline{\nabla I_f^{\,v}} = \frac{1}{S_I} \iint \nabla I_f^{\,v}(x^{\varphi}, y^{\varphi}) dx^{\varphi} dy^{\varphi}, \tag{6}$$

where $S_I = mn$ is the image area.

The gradient allows for the quantitative evaluation of the non-uniformity degree of the surface analysed along the coordinate axes [6]. A low mean value of the gradient testifies to an insignificant change in the intensity along the given axis of the image. In practice this means the uniform picture of the ordered structures in a certain direction [7] and points to the coordinate axis, which corresponds to the prevailing direction of the defect propagation.

The most general informative parameter, which allows evaluating the specimen damage by the obtained image, is the relative area of morphological formations:

$$S_d = \frac{S}{m \cdot n} \cdot 100\%, \tag{7}$$

where *S* is the number of pixels of the ordered structures in image *I*.
The distribution of the ordered structure elements along axes $(x^{\varphi}, y^{\varphi})$ of the image is described by vertical H_v and horizontal H_h histograms [8]:

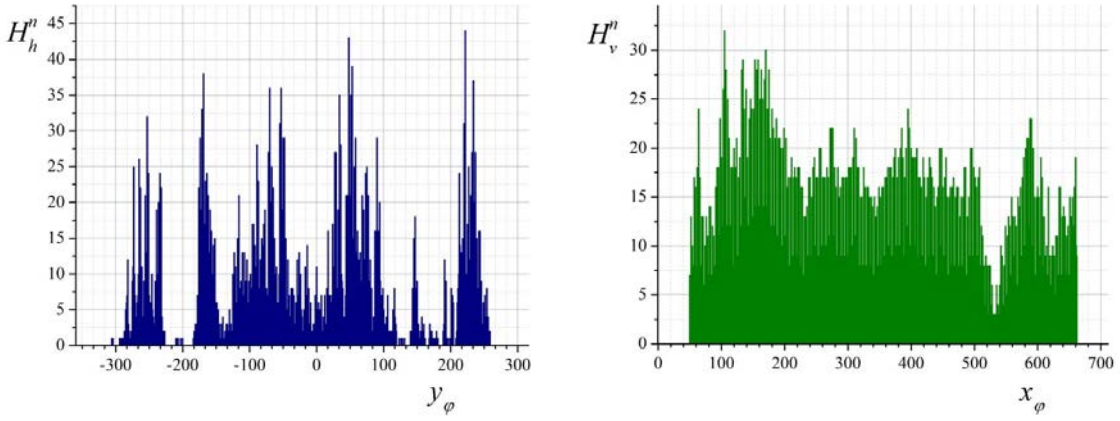
$$H_h(y^{\varphi}) = \sum_{x^{\varphi}=1}^{m\varphi} I(x^{\varphi}, y^{\varphi}), \quad H_v(x^{\varphi}) = \sum_{y^{\varphi}=1}^{n\varphi} I(x^{\varphi}, y^{\varphi}), \tag{8}$$

where $m\varphi, n\varphi$ are the image dimensions in the coordinate system $(x^{\varphi}, y^{\varphi})$ along axes x^{φ} and y^{φ}, respectively.

Since after the turn of the coordinate system the image cross-section becomes different for different values x^{φ} (or y^{φ}), the histograms were normalised to make possible the comparative analysis:

$$H_h^n(y^{\varphi}) = \frac{H_h(y^{\varphi})}{d_I(y^{\varphi})} \cdot 100\%, \quad H_v^n(x^{\varphi}) = \frac{H_v(x^{\varphi})}{d_I(x^{\varphi})} \cdot 100\%, \tag{9}$$

where $d_I(y^{\varphi})$, $d_I(x^{\varphi})$ are the image dimensions for coordinates y^{φ} and x^{φ}, respectively.



a b

Figure 4: Normalised horizontal H_h^n (a) and vertical H_h^n (b) histograms for the image of the polycrystalline fatigue sensor surface

Each element of the histogram contains a number of pixels, which correspond to the objects of the ordered relief structures in a certain direction of the image analysed. The histogram functions contain the basic information about the distribution of the ordered structures along the coordinate axes of the image [8].

The normalised histograms for the image of the polycrystalline aluminum fatigue sensor surface (Fig. 1,b) are shown in Fig. 4. It should be noted that the horizontal histogram is characterised by the clearly defined peaks, which correspond to blocks of the elongated relief elements. At the same time, the vertical histogram is characterised by a much more uniform shape, which indicates the absence of the clearly defined linear elements in this direction.

The quantitative evaluation of the histogram view (8) was performed based on the spectral analysis of its functions. Using the fast Fourier transformation the histogram functions were presented in the form of the row:

$$H_h^n(y^\varphi) \approx \sum_{k=0}^{Kh} A_{hk} \cos(2\pi \frac{k}{n} y^\varphi - \vartheta_h), \quad H_v^n(x^\varphi) \approx \sum_{k=0}^{Kv} A_{vk} \cos(2\pi \frac{k}{m} x^\varphi - \vartheta_v) \tag{10}$$

The number of harmonics of the K_h, K_v array was chosen in such a way as to ensure that the accuracy of presenting the histogram function in the form of the sum of harmonics was not below the limit value of ε.

$$\left| H_h^n(y^\varphi) - \sum_{k=0}^{Kh} A_{hk} \cos(2\pi \frac{k}{n} y^\varphi - \vartheta_h) \right| \le \varepsilon, \quad \left| H_v^n(x^\varphi) - \sum_{k=0}^{Kv} A_{vk} \cos(2\pi \frac{k}{m} x^\varphi - \vartheta_v) \right| \le \varepsilon \tag{11}$$

The mean amplitudes of the spectrum of functions of the horizontal and vertical histograms A_{ah}, A_{av} were chosen as the informative parameters:

$$A_{ah} = \frac{1}{K_h} \sum_{k=0}^{Kh} A_{hk}, \quad A_{av} = \frac{1}{K_v} \sum_{k=0}^{Kv} A_{vk} \tag{12}$$

The mean amplitude of the spectrum allows for the quantitative evaluation of the surface relief elements orientation along the image axes. Its higher values correspond to the greater degree of damage along the given axis. So, by comparing the values of A_{ah} and A_{av} it is also possible to obtain information about the prevailing direction of propagation of surface defects.

The availability of the pair of generalized characteristics – mean gradients G_h, G_v and mean spectrum amplitudes A_{ah}, A_{av} – allows obtaining the complex integrated characteristic of the analysed image in two mutually perpendicular coordinate directions [9].

4. Summary

The algorithm for the integral evaluation of the surface condition is proposed, which allows determining the condition of the deformation relief under regular and programmed loading, and the main regularities in its evolution.

For the quantitative evaluation of the surface condition it is proposed to use a multitude of integral parameters: the general area of damage, mean gradient along the coordinate axes, and the mean amplitude of the histogram function spectrum.

Determining the main regularities in the fatigue damage accumulation allowed obtaining new data on localisation of plastic strain in the fatigue sensor, which provides for an increased accuracy of evaluation of the aircraft structure condition.

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