UDK 620.178.3:669.715 ISSN 1580-2949
Original scientific article/Izvirni znanstveni članek MTAEC9, 47(3)357(2013)

AUTOMATED DIAGNOSTICS OF DAMAGE TO AN ALUMINUM ALLOY UNDER THE CONDITIONS OF HIGH-CYCLE FATIGUE

AVTOMATIZIRANA DIAGNOSTIKA POŠKODBE ALUMINIJEVE ZLITINE PRI VISOKO-CIKLIČNEM UTRUJANJU

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Prejem rokopisa – received: 2012-10-02; sprejem za objavo – accepted for publication: 2012-11-12

An identification and quantitative analysis of the deformation relief of the aluminium alloy for an aircraft construction based on a digital-image processing has been performed. The behaviour of defects has been assessed on the basis of diagnostics results for individual stages of the deformation process. It has been established that the individual stages of the damage-accumulation process are characterised by the values of integral-image parameters. Based on the consecutive processing of the data on the surface cyclic deformation, the main regularities of the propagation of defects have been found. Theoretical preconditions have been substantiated and experimental results obtained.

Keywords: fatigue, surface, digital image, diagnostics, accumulated damage, defect propagation, evaluation

Identificirali in kvantitativno analizirali smo relief deformirane površine aluminijeve zlitine za gradnjo letal. Temelj obojega je izdelava digitalne podobe površine vzorcev. Oceno vedenja defektov omogočajo rezultati diagnostike posameznih stopenj deformacijskega procesa. Ugotovili smo, da so te stopnje med akumulacijo poškodbe značilne po vrednostih integralnih parametrov slike. Na osnovi zaporedne obdelave podatkov ciklične deformacije na površini smo ugotovili glavne zakonitosti pri širjenju defektov. Tako smo dokazali teoretične predpostavke in pridobili eksperimentalne podatke.

Ključne besede: utrujanje, površina, digitalna podoba, diagnostika, akumulirana poškodba, širjenje defekta, vrednotenje

1 INTRODUCTION

An analysis of the loading conditions of modern civil aircrafts, the existing methods for evaluating the accumulated fatigue damage, the peculiarities of fatigue damage of aviation structural materials and the results of the previous fatigue investigations allowed formulating an approach to solving the problem of a quantitative evaluation of the accumulated fatigue damage of the aircraft structural elements[1]. However, the technological complexity of many of the existing instrumental methods for evaluating the accumulated fatigue damage as well as their insufficient accuracy and reliability limit the use of these methods for practical purposes.[2]

The initial diagnostics of the contemporary aircraft-skin condition involves the search and identification of the fatigue damage using the visual-control methods. It is known that the incubation period of the fatigue damage accumulation is, in many cases, reflected in the visual signs, which determine the possibility of both qualitative and quantitative evaluations of the accumulated fatigue damage.[3] The quantitative evaluation of the accumulated damage at the initial stage of fatigue allows predicting the place and the time of a fatigue-crack appearance. At the stage of designing aviation equipment such a prediction reduces the cost of a full-scale fatigue tests significantly due to shortening their duration, and, at the stage of operation, it allows increasing the reliability of aircrafts and safety of flights.[4]

A deformation relief is formed on the surface of the cladding layer of aluminium alloys under the stresses corresponding to the loading conditions of many structural elements during operation and testing. Stress concentration causes a prior formation of the relief in the vicinity of riveting holes, glue-cooking points, etc., which are the areas of potential failures. A surface deformation relief is observed at several scale levels. Using the optical microscopy the signs of a relief can be observed at the meso- and macro-levels.[5]

The need for substantiating and implementing the objective indicators of the deformation-relief intensity as the characteristics of the accumulated fatigue damage is obvious. The solution of this problem, by means of an analysis of damaged-surface images, will be shown below. The dependencies that allow predicting the residual life are of the most practical importance. Such dependences can be obtained on the basis of the data on deformation-relief-parameter evolution.[6]

It is proposed herein to use the integral parameters obtained by analysing the investigated surface images.

They allow evaluating the fatigue damage of the aluminium alloy for the aircraft construction.

2 DEFORMATION-RELIEF-EVALUATION TECHNIQUE

The specimen geometry is shown in **Figure 1**; the specimen was tested with cantilever bending at $R = 0$, $\sigma_{max} = 147$ MPa. The analysis of the deformation relief was performed near the stress concentrator (a hole with a diameter of 1.0 mm).

In the process of testing we recorded the surface condition in the vicinity of the stress concentrator after an application of cyclic loading, the number of loading cycles necessary for the initiation of a fatigue crack with a length of 1.0 mm, and the number of loading cycles leading to a complete failure. The specimen surface condition was evaluated by analysing its photo images obtained in a series after a certain number of loading cycles. The images taken with a photo camera (**Figures 1b** to **d**) were transformed into grayscale images with the brightness function $I(x,y)$. The absolute values of horizontal and vertical gradients were calculated for every pixel of an image:

$$\nabla I_x(x,y) = \left|\frac{\partial I(x,y)}{\partial x}\right|, \quad \nabla I_y(x,y) = \left|\frac{\partial I(x,y)}{\partial y}\right| \tag{1}$$

where $x \in N_m$, $y \in N_n$ (m and n are the width and height of an image, respectively):

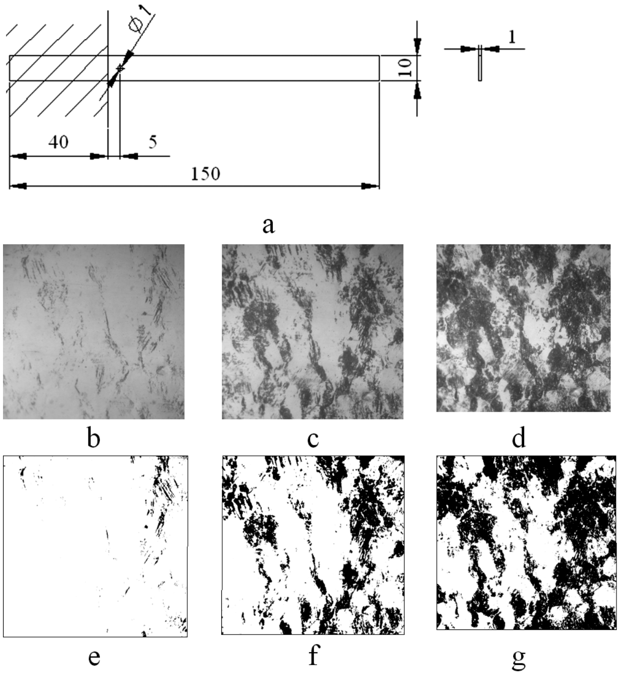

Figure 1: a) Scheme of the specimen investigated; examples of the deformation relief after 15, 100, 711 thousand loading cycles: b), c), d) initial image and e), f), g) binary image

Slika 1: a) Shema vzorca za preiskavo; primer reliefa deformirane površine po 15, 100, 711 tisoč obremenilnih ciklih: b), c), d) začetna slika in e), f), g) binarna slika

The mean values of horizontal and vertical gradients were used for a generalised evaluation of the condition of the surface investigated:

$$G_x = \overline{\nabla I_x} = \frac{1}{mn}\int_1^n\int_1^m \nabla I_x(x,y)\,\mathrm{d}x\mathrm{d}y$$
$$G_y = \overline{\nabla I_y} = \frac{1}{mn}\int_1^n\int_1^m \nabla I_y(x,y)\,\mathrm{d}x\mathrm{d}y \tag{2}$$

The gradient allows determining the predominant direction of the defect propagation and the nonuniformity degree of the surface investigated.[7] A low mean value of the gradient indicates an insignificant variation of intensities along the given axis of an image. In practice this shows a more uniform picture of the deformation relief in a certain direction[8] and indicates the coordinate axis that corresponds to the predominant direction of the defect propagation. In order to enhance the informative features corresponding to the elements of the damaged surface, binary transformation was applied to the obtained grayscale images.[9] This resulted in black-and-white images of the damaged surface with the intensity function IB, in which white pixels correspond to the background and black ones to the objects of the deformation relief (**Figures 1e** to **g**). The most general parameter that allows evaluating the degree of specimen damage using the obtained images, is the relative area of defects:

$$S_d = \frac{S}{m \cdot n} \cdot 100\% \tag{3}$$

where S is the number of deformation relief pixels in an IB image.

The distribution of deformation relief elements along the image axes is described with horizontal H_x and vertical H_y histograms:[8]

$$H_x(y) = \sum_{x=1}^{m} I(x,y), \quad H_y(x) = \sum_{y=1}^{n} I(x,y) \tag{4}$$

Each element of a histogram contains a number of pixels that correspond to the objects of the deformation relief, in columns and lines of the image analysed, respectively. Histogram functions (4) contain the basic information about the distribution of the deformation relief along the coordinate axes of an image.

For a generalised evaluation of the surface damage based on histograms it is proposed in[8] to use the mean values of histograms $\mu_x = S/n$ and $\mu_y = S/m$ (where S is the general number of black pixels). However, it is reasonable to use these parameters during multiple measurements under similar conditions with a permanent rectangular watch window. During laboratory testing of different specimens, especially under different conditions of the surface defect nucleation, the mean values of histograms contain little information. In addition, in the case of a rectangular watch window the values of μ_x and μ_y are scaled differently (relative to the image dimensions) and are inconvenient for a comparison, while in the case of a square watch window they become similar.

For a quantitative evaluation of the histogram view (4) a spectral analysis of the functions was performed. Using the fast Fourier transformation the histogram functions were presented in the form of a row:

$$\begin{aligned} H_x(y) &\approx \sum_{k=0}^{K_x} A_{xk} \cos\left(2\pi \frac{k}{n} y - \varphi_x\right) \\ H_y(x) &\approx \sum_{k=0}^{K_y} A_{yk} \cos\left(2\pi \frac{k}{n} x - \varphi_y\right) \end{aligned} \tag{5}$$

The number of the harmonics of histograms K_x and K_y was chosen in such a way as to ensure that the accuracy of presenting a histogram function as a sum of harmonics is not lower than the limit value of ε:

$$\begin{aligned} \left| H_x(y) \approx \sum_{k=0}^{K_x} A_{xk} \cos\left(2\pi \frac{k}{n} y - \varphi_x\right) \right| &\le \varepsilon \\ \left| H_y(x) \approx \sum_{k=0}^{K_y} A_{yk} \cos\left(2\pi \frac{k}{n} x - \varphi_y\right) \right| &\le \varepsilon \end{aligned} \tag{6}$$

The mean amplitudes of the spectrum of the functions of the horizontal A_{ax} and vertical A_{ay} histograms were taken as the informative parameters:

$$A_{ax} = \frac{1}{K_x - 1} \sum_{k=1}^{K_x} A_{xk}, \quad A_{ay} = \frac{1}{K_y - 1} \sum_{k=1}^{K_y} A_{yk} \tag{7}$$

The mean amplitude of the spectrum yields the quantitative evaluation of the damage propagation along the image axes. Its higher values correspond to a higher degree of damage along the given axis. Thus, while comparing the values of A_{ax} and A_{ay} it is possible to get information about the size and predominant direction of the surface-defect propagation.

The presence of the pairs of generalized characteristics – the mean gradients G_x, G_y and the mean amplitudes of the spectrum A_{ax}, A_{ay} – allows obtaining the complex integrated characteristics of the image analysed in two, mutually perpendicular, coordinate directions.

3 REGULARITIES IN DAMAGE ACCUMULATION

Cyclic loading forms a deformation relief on the surface of structural aluminium alloys, the intensity of which indicates the level of the accumulated fatigue damage.[10] The relief of this type was observed on both the standard specimens for the fatigue tests in a broad range of loading conditions and the specimens prepared from the skin of the An-24 aircraft; both were tested under stresses close to the operational ones.[1–3] The results of the investigations carried out using the methods of optical and electronic microscopy show the appropriateness of using the deformation-relief term and applying it as a diagnostic parameter of fatigue damage.[1,2]

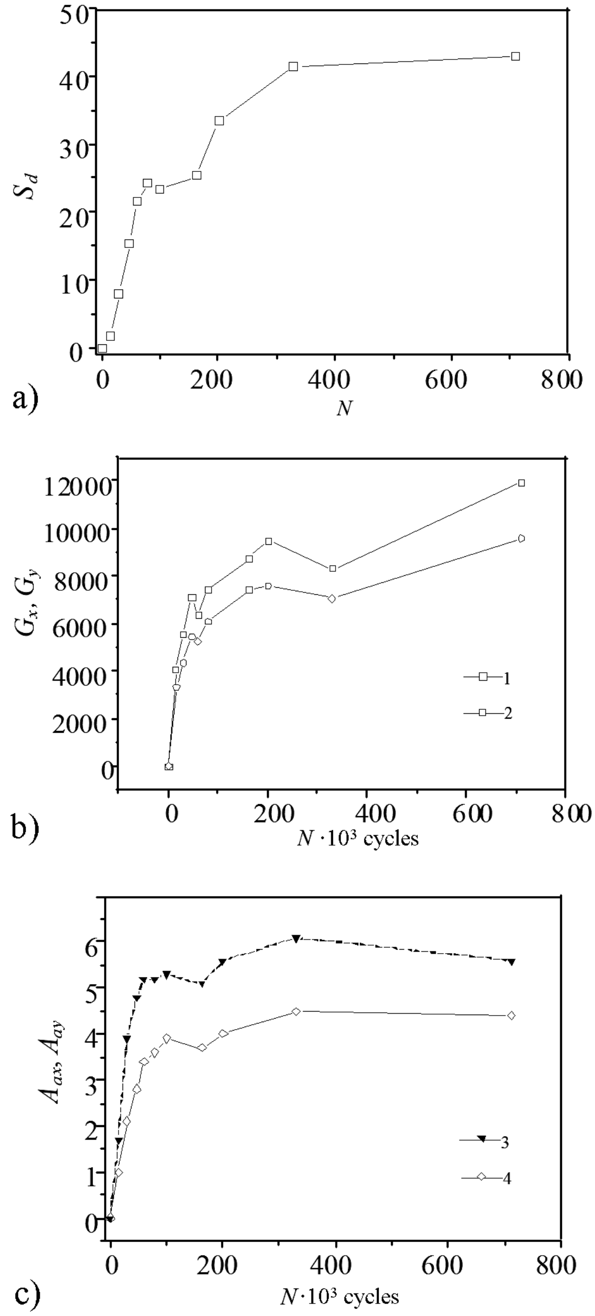

Figure 2: Dependence of integral parameters of deformation relief on: a) cyclic loading of a specimen, N: general area of defects S_d, b) mean horizontal and vertical gradients G_x and G_y, c) mean amplitudes of the spectrum, A_{ax} and A_{ay}

Slika 2: Odvisnost integralnih parametrov reliefa utrujenosti od: a) ciklične obremenitve vzorca N: skupna površina defektov S_d, b) povprečen horizontalni in vertikalni gradient G_x and G_y, c) srednja amplituda spektra A_{ax} and A_{ay}

Figure 2 shows the dependence of the calculated integral image parameters on the number of loading cycles. An increase in the S_d parameter indicates an increase in the degree of damage to the surface investigated. According to the experimental data, in the cases of up to 100,000 loading cycles, fast growing surface defects take place (**Figure 2a**). At the same time, after 100,000 loading cycles the deformation relief changes insignificantly.

The quantitative analysis of the kinetics of the changes in the deformation-relief orientation during cyclic loading of the aluminium alloy is performed. It is found that cyclic loading of 80,000 cycles causes a formation of a complex system of shears on the specimen surface. At this stage, an intense saturation of the surface with deformation shears takes place. Individual crystal blocks and their conglomerates sometimes ascend and sometimes descend above the surface, while their formations coalesce in groups and the sizes of defects increase gradually. This dynamic chaos is a depiction of the dynamic, cooperative dislocation processes at the micro- and meso-levels.[1,5] Nearly identical values of the gradients during the first phase of the investigation reflect the chaotic disorderly process of defect nucleation.

Later on the relief acquires an orderly orientation. Lower values of the vertical gradient (as compared to the horizontal one) show that along the vertical axis the picture of the deformation relief is more uniform, while along the horizontal axis sharper changes in the image intensity are observed. Thus, lower values of the gradient correspond to the direction, along which the areas of the surface damage stretch. A monotonous increase in the G_x and G_y parameters confirms the results obtained earlier,[11] indicating self-similarity and scaling of the formed deformation structures. The mean amplitudes of the spectrum of histogram functions A_{ax} and A_{ay} (**Figure 2c**) duplicate, to a certain extent, the dependence presented in **Figure 2a**; however, they allow characterising the surface failure process in two coordinate directions. Higher values of the vertical amplitude indicate a more significant damage in this particular direction.

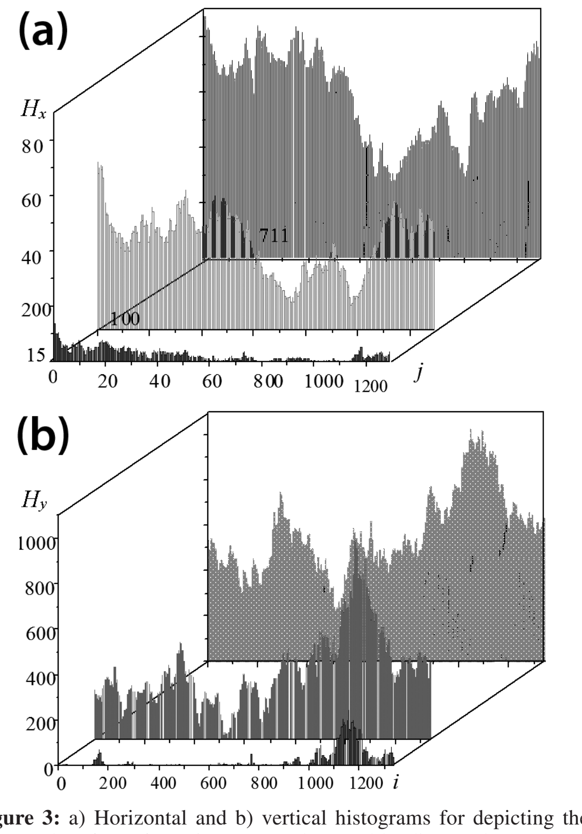

Figure 3: a) Horizontal and b) vertical histograms for depicting the deformed surface after 15, 100, 711 thousand loading cycles
Slika 3: a) Horizontalni in b) vertikalni histogram za opisovanje deformirane površine po 15, 100, 711 tisoč obremenilnih ciklih

The quantitative parameter of fatigue failure is found and it allows assessing the surface condition and the defect propagation direction within the section analysed based on the analysis of the surface saturation with visual signs of the deformation relief (**Figure 3**).

The chosen diagnostic parameter of damage and the technique of its quantitative evaluation allow considering the developed method as the express diagnostic of fatigue failure.

4 GRADED NATURE OF THE DEFORMATION-RELIEF DEVELOPMENT

The first stage is the fast accumulation of defects on the surface analysed. The structural non-uniformity causes a formation of residual stress fields, which relax partly by means of forming sliding bands, extrusions and intrusions in the individual grains of the material[12]. Characteristic structural traces of the localisation are observed in macro extrusions in the form of the aggregates of "ridges" ("hills"). An intense formation of the deformation relief takes place. This stage accounts for approximately 15–20 % of the general number of cycles to the onset of crack formation.

The second stage is the slowing down of microplastic shears of the grains of the material, coalescence of individual sections of the deformation relief and saturation of the system. Although the damage accumulation process (deformation relief) is slowed down at this stage as compared to the previous one, its course is quasistationary. It is this that allows using it for technical diagnostics of a damaged-surface condition with a view to predicting the limit state. The limit state refers to the nucleation of a fatigue crack with the length of 1.0 mm that can be identified by means of optical control. The limiting value of damage parameters was considered as the last one in the row of values that were obtained before the moment of the fatigue-crack formation.

5 CONCLUSIONS

A technique has been developed for evaluating the aluminium-alloy surface condition by analysing its image and calculating its integral parameters, including the general area of damage, the mean gradients along the coordinate axes, and the mean amplitude of the spectrum of histogram functions along the coordinate axes. The basic factor that allows using the proposed technique is the saturation of the material surface with the visual signs of the relief that are detected with the methods of optical microscopy. For the quantitative characteristic of the relief, the damage parameters can be used and they allow analysing the variation of spatial orientation of the defects caused by a deformation within the surface, on which the signs of localised strain are absent.

The main regularities in the accumulation of fatigue damage on the surface of an aluminium alloy have been established. The possibility of using the developed technique for determining the accumulated fatigue damage under high-cycle fatigue is substantiated.

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