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FATIGUE LIFE PREDICTION BY THE STRUCTURALLY SENSITIVE DAMAGE INDICATOR

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The investigations of the new fatigue sensor that was carried out at the wide range of cyclic loads conditions show the ability of the indicator application in Structural Health Monitoring systems of planes, bridges, vessels, and other structures. Accumulated fatigue damage may by estimated by the intensity of deformation relief, i.e. by its extrusion/intrusion and persistent slip bands structures on the indicator surface.

Keywords: alelad aluminum alloys, deformation relief, fatigue, fatigue indicator.

Розглянуто результати дослідження нового індикатора втоми, проведених в широкому діапазоні режимів циклічного навантажування. Показано можливість застосування індикатора в системах контролю технічного стану літаків, мостів, кораблів та інших конструкцій. Накопичене втомне пошкодження визначено за інтенсивності деформаційного рельєфу поверхні, який формують екструзії, інтрузії і сталі смуги ковзання на поверхні індикатора.

Ключові слова: втома, деформаційний рельєф, індикатор втоми, плакований алюмінієвий сплав.

Introduction

Metal fatigue is still one of the main reasons of unforeseen crashes of planes, vessels, bridges and many others engineering structures.

Components that fail by fatigue undergo three stages of damage:

a) fatigue crack initiation;

b) fatigue crack propagation;

c) sudden final failure.

It is obvious that the quicker one can reveal the initial stage of fatigue the less probability of disastrous failure is.

A set of diagnostic methods use fatigue sensors, mounted on the surface of the object to be inspected. The sensors subjected to the spectrum of operating cyclic loads, change their state or may be even destroyed and in such a way indicate the degree of damage in the tested structural element.

Our investigations show that quantitative estimation of accumulated fatigue damage may effectively be conducted by the computer-aided optical analysis of the surface state of the metal fatigue indicator, attached to the investigated units.

Evolution of the aluminium extrusion/intrusion structure under fatigue

New indicator of fatigue damage is based on the researches of the extrusion/intrusion and persistent slip bands structures on the surface of aluminium under fatigue.

At the initial stage of our research and development the single-crystal fatigue damage indicator was created at the National Aviation University in cooperation with Ukrainian Physic Metal Institute [1–3].

The diagnostic parameter of the single-crystal sensor is the density of slip lines on the sensor's surface. The evolution of slip lines density on the single-crystal sensor surface was investigated under the regular cyclic loading and some regimes of the program loading. In all cases the relationship between density of slip lines and number of cycles of loading and level of strain was observed. Moreover, it was shown, that single-crystal sensors can be applied for the assessment of the damage both under cyclic and static loading.

Currently, the surface deformation relief of the alclad aluminium alloys under fatigue has been investigated by the computer-aided light

microscopy, scan and transmission electron microscopy.

As far as the presented cycle of researches was aimed at the development of the aircraft fatigue monitoring system, aluminium alloys D16AT, V95, 2024T3 and 7075T6 have been chosen for the experiments. These materials are widely used for modern aircraft skin manufacturing in Ukrainian, Russian and Western aircraft industry.

Flat specimens with a hole in the center were used in fatigue test procedure. Such stress concentrator indicates the point for surface state investigation. The specimen is 1,5 mm and the diameter of the hole is 4 mm. All investigations of the surface have been conducted close to the stress concentrator, where stress level is maximum.

Special computer-aided optical equipment has been designed for deformation surface relief monitoring. The main objective was to use standardized systems of mass production with stable characteristics and relatively low in cost. The present investigation of deformation relief and the quantitative estimation of the accumulated fatigue damage have been conducted with the system containing metallographic light microscope with the enlargement from 150 to 350, digital camera and portable PC.

The three-dimensional character of observed pattern and its correspondence to the known scheme of intrusions and extrusions formation (fig.1, 2) have been confirmed by means of Scanning Electron Microscopy (SEM) investigation by using microscope Zeiss DSM950.
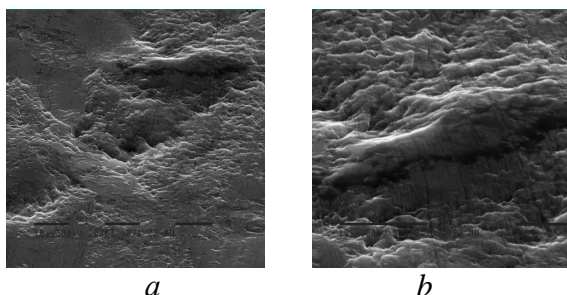
As it is seen from the fig. 1 the same objects reveal new features at different angles of the observation. The specimen presented on the fig. 1, 2 was tested under the maximum stress level 231,1 MPa, stress ratio R = 0 and frequency 11Hz.

The number of cycles applied to the specimen is $N = 10^5$.

The fig. 2 reveals typical structural components of the deformation relief, namely: extrusions, intrusions, persistent slip bands.

Images of cyclically loaded specimen surfaces have been processed by special software. The developed program gives the possibility to determine quantitatively the damage parameter D. Such parameter is equal to the area of specimen surface occupied by deformation marks divided by the total considered surface [4].

The researches have been carried out within the wide range of stress conditions, including axial tension and bending at different stress ratio. A set of experimental curves that show the dependence of accumulated damage parameter D on the number of cycles have been obtained. All curves and those presented below have been obtained by the approximation with log function.

As an example the result of fatigue test of D16AT specimens and damage monitoring under axial tension with the maximum stress of 76,9 MPa; 81,7 MPa; 96,2 MPa; 105,8 MPa; 115,4 MPa; 129,8 MPa, 134,6 MPa and stress ratio R = 0 and frequency are presented.
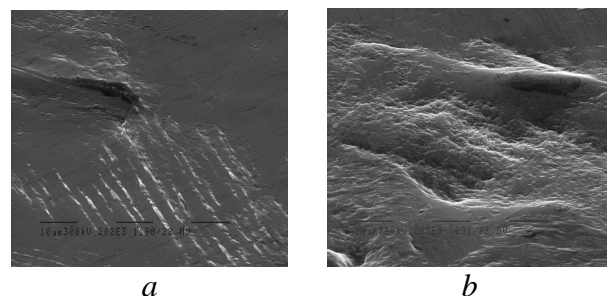

a   *b*

Fig. 1. Deformation relief at the investigation at different angles of observation and different enlargements:
a – x 2020;
b – x 5000

a   *b*

Fig. 2. Structural components
of the deformation relief:
a – persistent slip bands;
b – extrusions and intrusions

It expresses the relationship between the damage parameter D and current number of cycles N_i (fig. 3).
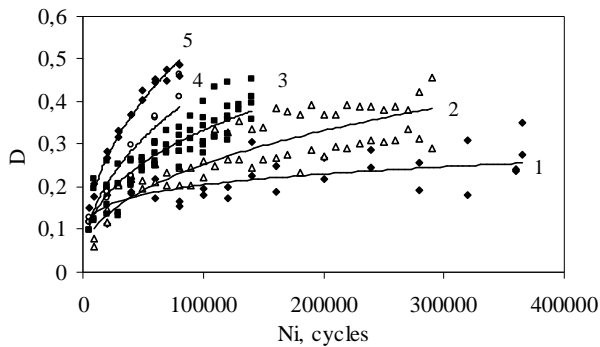

Fig. 3. Evolution of damage parameter D on the surface of alclad aluminum alloy D16AT under cyclic loading:

1 – σ_{max}=76,9 MPa;
2 – σ_{max}=81,7 MPa;
3 – σ_{max}=96,2 MPa;
4 – σ_{max}=115,4 MPa;
5 – σ_{max}=134,6 MPa

The tests were stopped after the nucleation of 1,0 mm fatigue crack as it has been considered as the critical state condition.

The investigation of deformation relief evolution under different maximum stresses shows the sensitivity of damage parameter to the value of the maximum stress level.

The aim of the following test was to justify experimentally the possibility of quantitative estimation of accumulated fatigue damage by damage parameter D under loadings with different stress ratio.

Specimens of aluminium alloys D16AT have been loaded by bending under the wide range of stresses ratio at frequency 25 Hz.

Fig. 4 shows the evolutions of damage parameter *D* under the loading process of specimens, tested by bending under the maximum stress of the cycle $\sigma_{max} = 234,5$ MPa and the different stress ratio R.

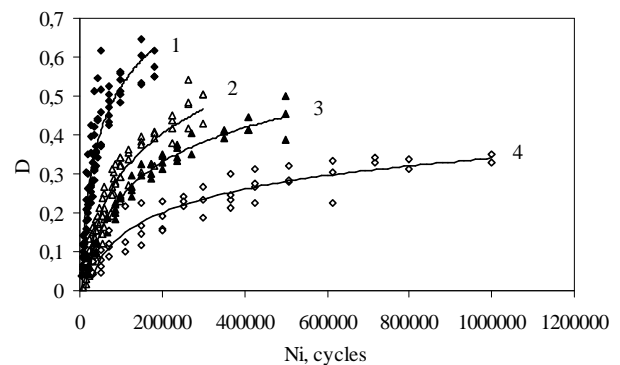The results presented on fig. 4 prove the sensitivity of parameters of deformation relief to the stress ratio.

Fig. 4. Evolution of damage parameter *D* during asymmetrical loading process under stress ratio:

1 – *R* = 0;
2 – *R* = 0,42;
3 – *R* = 0,5;
4 – *R* = 0,6

The search of the additional quantitative criteria for deformation relief has led to fractal geometry [5], which is wildly used nowadays at solving the material science problems. It was proved that the application of fractal geometry improves the method of optical diagnostic of surface state and prediction of residual fatigue life of structural units made of alclad aluminium alloy [6].

The fractal geometry uses several kinds of fractal dimensions as the quantitative parameters for the description of irregular object shape. After system investigation of the deformation relief fractality, the fractal dimension Dp/s has been chosen. Such dimension can be calculated taking into consideration the ratio of the deformation relief cluster perimeters and area.

The fractal dimension Dp/s appears to be most informative parameter of the surface relief patterns shape. Typical plot illustrating relationship between the fractal dimension Dp/s and number of cycles presented on fig. 5.

Conceptual design of the new fatigue indicator

The above described approach to the aluminium fatigue monitoring can be applied for direct diagnostic of structural material state and for the fatigue monitoring by the indicators made of correspondent metal.
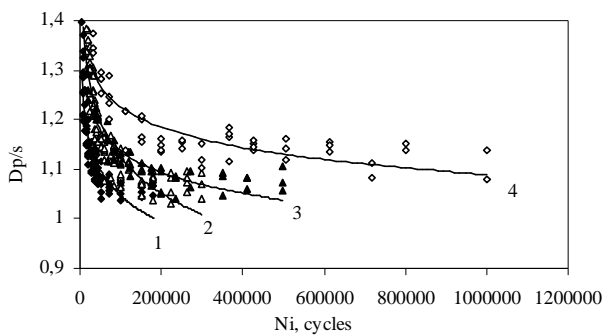
Fig. 5. Relationship between the fractal dimension Dp/s and number of cycles under stress ratio:
1 – *R* = 0;
2 – *R* = 0,42;
3 – *R* = 0,5;
4 – *R* = 0,6

The structurally sensitive damage indicator is made of alclad aluminum alloy D16AT. Such choice is caused by the next reasons:

– the possibility of quantitative estimation of accumulated fatigue damage by the parameters of deformation relief, which is formed on the surface of alclad layer under cyclic loading has been proved;

– aluminum alloy D16AT is the basic structural material, that is why it defines phenomenological community with the fracture processes in the sensor and in the most part of structural material of the aircraft.

Taking into account the wide spectrum of loading condition, it is obvious that a problem of the indicator sensitivity optimization in accordance with the actual loading of the elements, arises.

In the developed indicator the necessary rise of sensitivity is achieved by the redistribution of stress due to the corresponding distribution of stiffness along the length of indicator.

The local stress rise in the test portion of the indicator is defined by the relationship between the width of test portion and the overall dimensions. The test portion of the indicator does not contact with the surface of structural element. At the same time fatigue sensor must be fixed in the available design holes of the construction.

The experience of the previous applications of the fatigue damage specimen-witness in aviation was used for the definition the place and the method of the indicator installation.

The specimen-witness on airplanes can be placed at the rear wing spar of the wing.

The quality of the sensor surface is reached by the mechanic and electrolytic polishing. It is necessary for the light microscopic analysis of deformation relief, which is formed on the surface of sensor.

The application of finite element analysis permits to solve a problem of the sensor's geometry optimization for required sensitivity.

Among the main stages of simulation is the simulation of team-work of the alclad layer and structural alloy. It is very significant problem because the materials of alclad layer and basic alloy have essentially different mechanical characteristics.

The attachment of the indicator to the specimen (fig. 6) for fatigue tests and their team-work under cyclic loading has been also simulated.
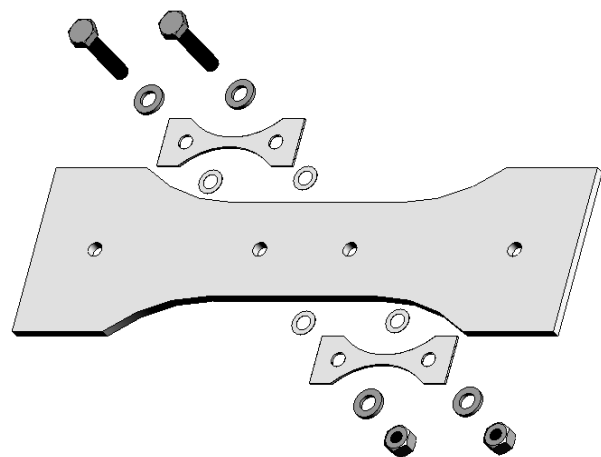

Fig. 6. 3D image of the sensor attachment to the specimen for fatigue test

In the mentioned tests the sensors were installed on each side of structural components. Thereby such scheme helps to provide the symmetrical loading of the sensors and to receive more information about their damage.

The results of the indicator surface state monitoring

The conducted fatigue tests conformed the ability of the fatigue indicators application for the fatigue damage monitoring of aviation components.

Deformation relief which is formed on the surface of the indicator in the test portion actually is the system of the extrusions, intrusions, persistence slip bands, i.e. the evolution of the sensor surface state is similar to the processes, previously investigated on the surface of alclad aluminium alloys specimens near the stress concentrators (fig. 7).
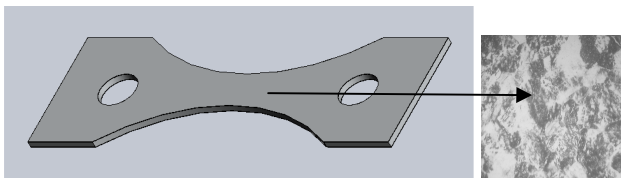

Fig. 7. Optical image of the deformation relief on the sensor's surface. N=20000 cycles, stress in the sensor's working area $\sigma_{max} = 234,5$; R = 0

It was shown in papers [4; 6] that the deformation relief can be described by some quantitative parameters, namely: damage parameter D, fractal dimensions of deformation relief clusters Dp/s.

The strong relationship between the selected parameters and number of cycles has been revealed.

Taking into account that the both parameters, namely D and Dp/s indicate the accumulated fatigue damage it was proposed to use multiple regression model for the residual life prediction:

$$N_{res.} = A + B \log D + C \log Dp/s,$$

where $N_{res.}$ – number of cycles to the fracture;

A, B, C – constants;

D – damage parameter;

Dp/s – fractal dimension.

The test conducted under the different loading conditions has shown that the accuracy of above mentioned multiple regression model can be expressed by the coefficient of determination R^2 in the range from 0,75 to 0, 95.

Conclusions

The presented results have shown the ability of the fatigue indicator application for the estimation of fatigue damage of metal structures.

The system of the extrusion/intrusion and persistent slip bands on the sensor's surface is considered as the indicator of accumulated fatigue damage.

The indicator sensitivity is defined by the local stress multiplication and it may be controlled by the geometry of test portion with the help of finite element analysis.

The presented indicator may be adapted for planes, bridges, vessels and others engineering structures.

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