FATIGUE SENSOR FOR STRUCTURAL HEALTH MONITORING

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ABSTRACT: Increase of metal structures service life and the general tend for economy of metal keep the fatigue problem actual. Variety of designs, construction materials, loading conditions, as well as different requirements for service life of modern metal structures determine the necessity of wide spectrum of techniques for structural health monitoring. Fatigue damage of metal structures may be estimated by the application of sensors with the surface pattern indicating the accumulated fatigue damage. First, such sensors have been developed for aircraft structures fatigue monitoring. It was stimulated by very high requirements to the aircraft reliability and strength. Carried out investigations of fatigue sensors at the wide range of cyclic loads conditions show the ability for their application in Structural Health Monitoring systems of planes, bridges, ships and other structures, subjected to the action of repeated loads. On the first stage of the research and development activity the single crystal sensors were proposed. These researches have helped to create phenomenological basis for the development of the new generation of surface relief fatigue sensors. Now, after numerous investigations the efficiency of polycrystalline sensors has been proved. Such sensors are the specimen-witness attached to the investigated part of construction. For polycrystalline sensors the accumulated fatigue damage may by estimated by the intensity of deformation relief, i.e. by its extrusion/intrusion structures and persistent slip bands on the surface. Fractal analysis of the surface patterns based on box-counting method proved the efficiency of fractal geometry application for quantitative description of such structures. Appropriate materials for fatigue sensors manufacturing are well known aluminum alloys 2024T3, 7075T6, covered by the layer of pure aluminum. This layer acts as an indicator of fatigue damage because the deformation relief appears on the surface under the action of repeated loads. The evolution of deformation relief parameters on the sensors surface is determined by the process of the construction's fatigue damage accumulation. For the investigation of deformation relief evolution and correspondent fatigue damage assessment the computer-aided optical system has been developed. The analysis of the optical images of the fatigue sensor surface state gives the data for mathematical models of construction residual life prediction. Finite elements method allows to optimize the geometry of sensors and to achieve necessary sensitiveness according to tasks of Structural Health Monitoring.

1 INTRODUCTION

Due to the development of analytical and tools methods of accumulated fatigue damage estimation the failure rate caused by metal fatigue has decreased last years. Nevertheless, metal fatigue is still one of the main reasons of unforeseen crashes of planes, ships, bridges and many engineering structures.

Components that fail by fatigue undergo three stages of damage: a) initiation of a fatigue crack; b) propagation of the fatigue crack; c) final sudden failure.

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

Fatigue analysis includes a set of theoretical and experimental procedures, but taking into account the complicated character of actual loading and the stochastic nature of metal fatigue, one may assume that at present only adequate instrumental diagnostic of accumulated fatigue damage can prevent unexpected failure of structural components.

There are two approaches to instrumental estimation of accumulated fatigue damage: a) application of fatigue sensors (indicators, specimen-witnesses); b) direct material state diagnostic.

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 computer-aided optical analysis of the surface state of the metal sensors, attached to the investigated units.

2 EVOLUTION OF THE ALUMINIUM EXTRUSION/INTRUSION STRUCTURE UNDER FATIGUE

New sensor of fatigue damage is based on the researches of the evolution of the aluminium extrusion/intrusion structure under fatigue on the surface of aluminium.

At the initial stage of our research and development efforts the single-crystal fatigue damage indicator was created at the National Aviation University in cooperation with Ukrainian Physic Metal Institute, Karuskevich et al. (1992, 1995, 2002). The diagnostic parameter for 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 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 presented cycle of researches was aimed on the development of the aircraft fatigue monitoring system, aluminium alloys D16AT, 2024T3 and 7075T6 have been chosen for experiments. These materials are widely used for manufacturing of modern aircraft skin in Ukrainian, Russian and Western aircraft industry.

Flat specimens with a hole in the center, in order to induce fracture localization were used in fatigue test procedure. Such stress concentrator indicates the point for surface state checking as well.

The thickness of the specimen is 1,5 mm and the diameter of the hole is 4 mm. These dimensions were chosen taking into account that sheets 1,5 mm thickness are used in many cases for aircraft skin production, where the 4 mm hole imitates a constructive hole for rivets. Riveted aluminum structures are found to vary degrees on virtually all aircraft. In aircraft structures rivets are used to joint sheets of the skin, or to mount skin on frames and stringers. The number of rivets in the structure of a modern 200 seat passenger airplane is more than 1,5 million. Thus, such kind of stress concentrator is typical.

All damage parameter measurements have been performed at the stress concentrator, where stress level is maximum.

Special computer-aided optical equipment has been designed for deformation relief monitoring. The main objective was to use standardized systems of mass production with stable characteristics and relatively low 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) have been confirmed by means of Scanning Electron Microscopy (SEM) investigation by using microscope Zeiss DSM950.

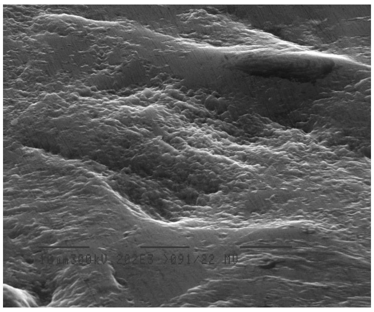

Figure 1. Extrusion/intrusion structure of the cyclically deformed aluminium.

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, Karuskevich et al. (2004).

Cyclic deformation test has been carried out with a hydraulic pulsating machine at frequency of 11 Hz. The shape of loading cycle is sinusoidal. The researches have been carried out in the wide range of stress conditions. A set of experimental curves that show the dependence of accumulated damage parameter 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 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 are presented. It expresses the relationship between the damage parameter D and current number of cycles N_i (Fig.2).

The tests were stopped after the nucleation of 1.0 mm fatigue crack as it has been considered as the critical state condition.

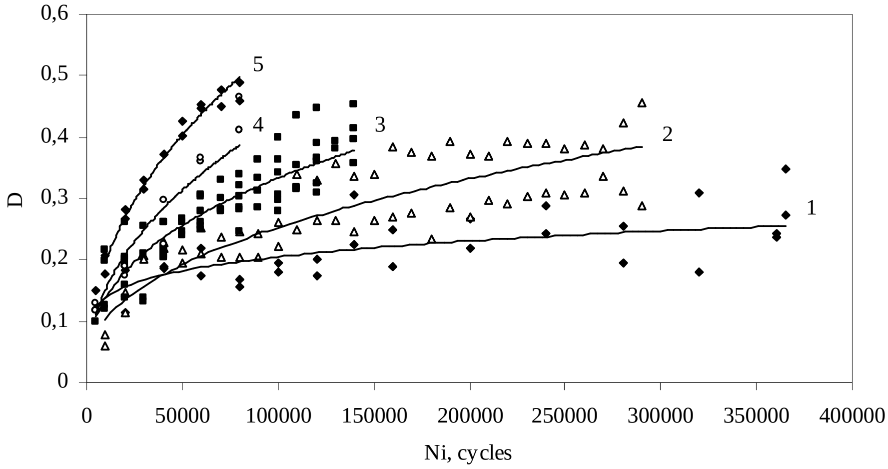

Figure 2. The evolution of damage parameter D on the surface of alclad aluminum alloy under cyclic loading: 1) σ_{max}=76,9 MPa; 2) σ_{max}=81,7 MPa; 3) σ_{max}=96,2 MPa; 4) σ_{max}=115,4 MPa; 5) σ_{max}=134,6 MPa.

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

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

Specimens of aluminium alloys D16AT, 2024T3 and 7075T6 have been loaded by bending under the wide range of stresses ratio at frequency 25 Hz.

Below the evolutions of damage parameter *D* under the loading process of specimens, tested by bending under the different stress ratio R are presented (fig. 3).

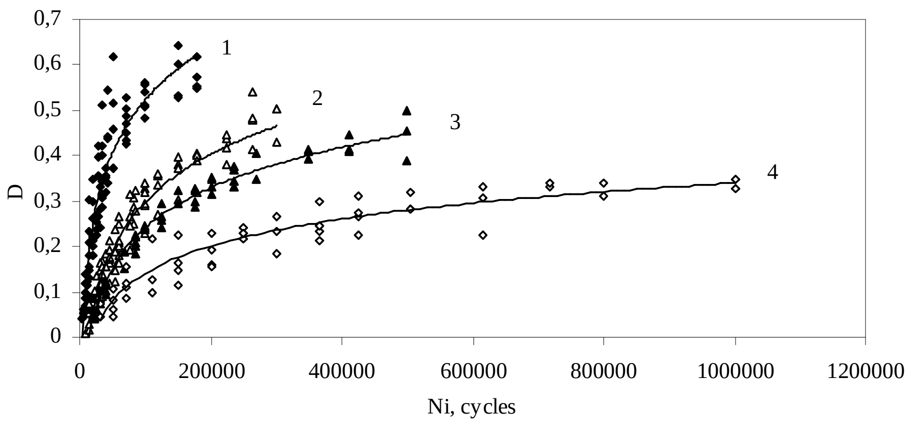

Figure 3. Evolution of damage parameter D during asymmetrical loading process under stress ratio: 1) R=0,2; 2) R=0,42; 3) R=0,5; 4) R=0,6.

The results presented at fig.3 prove the sensitivity of the deformation relief parameters to the stress ratio.

The search of the additional quantitative criteria for deformation relief has led to fractal geometry, Feder (1988), which is wildly used nowadays at solving the material science problems. Analysis of deformation processes results in application of fractal geometry which improves the method of optical diagnostic of surface state under the estimation of accumulated fatigue damage and prediction of residual fatigue life of structural units made of alclad aluminium alloy, Karuskevich et al. (2008).

3 CONCEPTUAL DESIGN OF THE NEW SENSOR

The described above approach to the aluminium fatigue monitoring can be applied for direct diagnostic of structural material state and for the fatigue monitoring by the sensor made of correspondent metal.

New fatigue sensor looks like a micro specimen for fatigue test (fig.4).

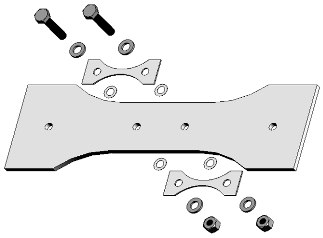

Figure 4. 3D image of the sensor attachment to the specimen for fatigue test

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

The application of the sensor with the effect of strain multiplication sometimes the only possible way to reflex operational loads with formation of corresponded effect. The basic requirements for the sensor with strain multiplication are: possibility of wide range of the multiplication coefficient change; compactness; reliability of fastening to the tested design element; minimization of the strain redistribution in the design elements due to the sensor fastening, etc.

The fatigue sensor is also made of alclad aluminum alloy D16AT. Such choice is caused by the next reasons:

- it has been proved 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;

- 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.

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

The local stress rise in the test portion of the sensor is defined by the relationship between the width of test portion and the overall dimensions. The test portion of the sensor is not contact with the surface of structural element. With all this going on, fatigue sensor must be fixed in the available design holes in the construction.

The experience of the previous applications of the fatigue damage specimen-witness in aviation was used for the place and the method of sensor installation definition. The specimen-witness on airplanes can be placed into the rear spar of the wing. The analysis of modern aircraft structures has shown the advisability of manufacturing basic model of sensor with the same length between the fixing points. 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 geometry optimization for necessary sensitiveness. Among the main stages of simulation is the simulation of team-work between the alclad layer and structural alloy. It is very significant and intricate problem because the materials of alclad layer and basic alloy have essentially different mechanical characteristics particularly elastic limit.

The junction of the sensor to the specimen for fatigue tests and their team-work under cyclic loading has been also simulated.

The sensors are installed on each side of structural elements. Thereby it helps to provide the symmetrical loading of sensors and to receive more information about their damageability. The final stage of the specimen-witness optimization is to get stress diagram and strain diagram and to determine the optimal sensor geometry.

4 THE RESULTS OF THE SENSOR'S SURFACE STATE MONITORING

The conducted fatigue tests have conformed the ability and advisability of the fatigue sensors application to the effect of stress multiplication for the fatigue damage monitoring of structural aviation elements.

Deformation relief which is formed on the surface of sensor in the test portion and the most stressed is the system of the extrusions, intrusions, persistence slip bands. 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.

It was shown in papers, Karuskevich et al. (2004, 2008), that the deformation relief can be estimated by some quantitative parameters, like these: damage parameter D, fractal dimensions of deformation relief clusters.

In fig. 5 the data of damage parameter evolution for two sensors with different local stress in their test portion under cyclic loading with the maximum stress 160 MPa in structural elements and the stress ratio is R=0 are presented . The first signs of deformation relief formation on the sensor surface have been founded after the 20000 cycles.

The close relationship between the damage parameter and number of cycles has been revealed. It allows to predict residual life of the structure by the deformation relief quantitative parameters.

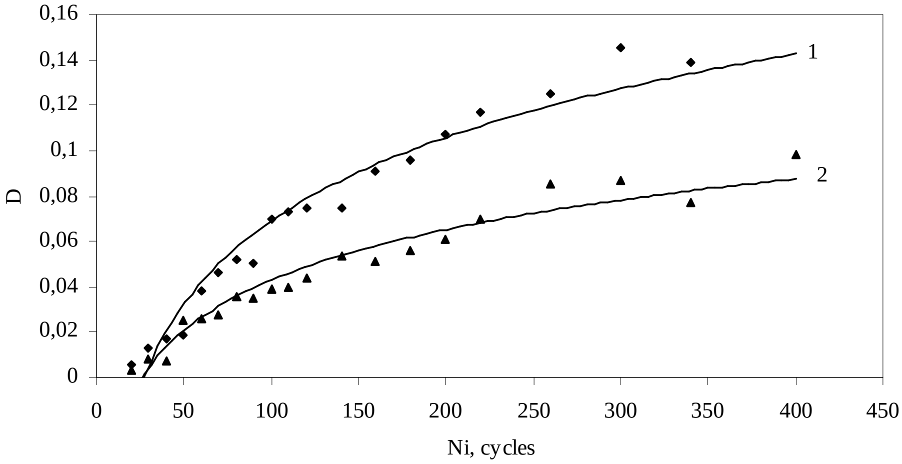

Figure 5. The evolution of damage parameter D for sensors of different sensitiveness: 1 – the maximum stress in the test portion of the sensor is equal to the σ_{max}=280,0 MPa; 2 – the maximum stress in the test portion of sensor is equal to the σ_{max} = 240,0 MPa.

4.1.1 References

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4.1.2 Conclusions

The presented results have shown the ability of the fatigue sensor application for the estimation of metal structures fatigue damage. The extrusion/intrusion and persistent slip bands on the sensor’s surface are considered as indicators of accumulated fatigue damage. The sensitiveness of sensor is defined by the local stress multiplication and it may be controlled by the variation of the geometry of test portion. The presented sensor would be adapted for planes, bridges, ships and others engineering structures.