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FOIL FATIGUE SENSOR FOR STRUCTURAL HEALTH MONITORING SYSTEMS

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The concept of foil fatigue sensor is presented. The deformation relief of the sensor surface is considered as an indicator of the fatigue damage. The quantitative parameter of the deformation relief intensity determined by the computer aided method is applied. The possibility to monitor fatigue damage of metal structures by the application of foil fatigue sensor is proved. The method to control sensitivity of the sensors is shown.

Introduction

Accumulation of fatigue damage is one of the main factors limiting the service life of metal structures, including civil aviation aircrafts. Fatigue monitoring of critical structural elements can prevent sudden failure and to consider individual history of loading in assessing the actual exhaustion of the service life.

The process of metal fatigue accompanied by a change of their properties at the micro-, mezo- and macro-scale levels, which allows application of a number of physical methods for quantitative assessment of the accumulated damage and the corresponding remaining life.

The most effective are methods of acoustic emission [1, 2], eddy currents [3], magnetic coercimetric [4] and others.

Estimation of accumulated damage is performed by the direct investigation of the state of the construction material and by the state of specimen-witnesses. These sensors are attached to the critical structural elements. Perceiving the operational range of loads, sensors indicate accumulated damage by the change of certain parameters of their state.

It should be noted that a number of sufficiently sensitive methods can’t be used to monitor the fatigue damage due to the nonmonotonic evolution of the recorded parameters [5].

Method, which is traditionally deserves trust of practical engineers, is the optical control. Optical method is used to detect various defects, including fatigue cracks.

Investigations conducted at the National Aviation University, have shown that the optical control allows monitoring of the process of fatigue damage in the incubation stage, i.e. long before the appearance of fatigue cracks.

Such a possibility is opened due to the fact that on the surface of many pure metals and some alloys as a result of repeating cycles deformation relief nucleates and develops.

Numerous studies of deformation relief, formed on the surface of single-crystal and polycrystalline aluminum have shown [6-7] that its evolution can be assessed qualitatively and quantitatively using a computer aided optical method of nondestructive testing.

For structural components made of alclad aluminum alloy it opens up the possibility of direct diagnostic of construction and evaluation of its damage.

In cases when on the surface of the structural material deformation relief is not formed or scale level of the defect structure of the surface does not allow usage of optical methods, the installation of the structurally-sensitive fatigue sensors is propsed, which surface state varies in accordance with the accumulated damage.

Thus, the created methodology of the accumulated fatigue damage estimation by the surface topography can be achieved in two ways: a) by the direct control of the structures components surface state if structural properties of the material ensure the formation and development of the surface deformation relief; b) by the use of structurally-sensitive fatigue sensors.

Fatigue sensor, made of aluminum alclad alloy D16AT, suggesting the possibility of adapting its sensitivity in accordance to the tasks of monitoring and loading conditions considered in the paper [8].

In the present paper the possibility of the application of foil fatigue sensor made of polycrystalline aluminum is discussed.

Material, dimensions, method for the sensor attachment

Previously [6] the possibility of fatigue sensors manufacturing from aluminum single crystals, grown in accordance with the Bridgman method was demonstrated. The complexity of the manufacturing process and, as a consequence, the high cost of such sensors has led to the search for alternatives.

Material appropriate for the structural-sensitive fatigue sensor producing is a technical aluminumAD-1 [9].

The thickness of the foil prior to treatment was 0.2 mm. Size of the sensor after the preparation of the surface to the optical control of 20.0 x 10.0 x 0.15 mm. Reducing of the thickness from 0.2 mm in the blank to 0, 15 mm in the sensor caused by its polishing.

In order to relieve internal stresses in the blanks of sensors their preliminary annealing is performed. The annealing temperature in the first stage of the study was 550 ° C. Duration of exposure at a given temperature for 2 hours. Heat treatment resulted in increased grain from 0.05 mm to 0.5 mm.

Necessary for optical analysis of deformation relief surface quality achieved by consistent preliminary mechanical polishing and electrolytic polishing.

Mechanical polishing was performed manually using diamond paste.

Electrolytic polishing was performed in the electrolyte, which comprises: 50% H_3PO_4, 39% H_2SO_4, 3% CrO_2, 8% H_2O. The current density of 15-20 A/dm^2; the temperature of the solution during polishing 75-85 ^{0}C.

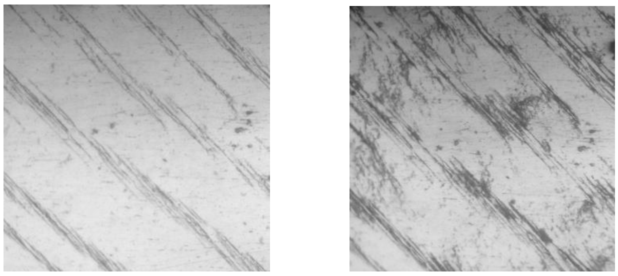
Fixing of the foil sensors was accomplished by multicomponent glue PASCO ® FIX based on ethyl cyanoacrylate acid. Experience of using cyanoacrylate based adhesives for deformation measurement in aircraft testing suggest the possibility of the glue use in the temperature range corresponding to the operating conditions of aircraft structures.

Diagnostic parameters

In the current series of investigations the foil sensor was mounted on a flat specimen of D16AT alloy, which was tested at a maximum stress of loading cycle σ_{max} = 180,0 MPa, loading frequency 11.0 Hz and stress ratio R=0. Tests were conducted on a standard test machine MUP-20. Monitoring of the surface state was carried out using light metallographic microscope MMR-4 with enlargement of 350^x.

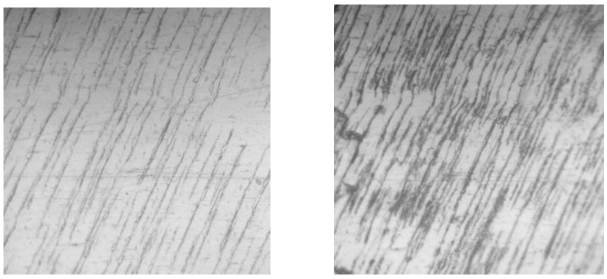
Figures 1 and 2 shows the development of the deformation relief in the two selected for control crystallites (grains).

As a result of the heat treatment the crystallite size was achieved at which at magnification 350^x there is only one grain is observed in the view spot.



a *b*

Fig.1. Deformation surface relief of the foil structurally-sensitive fatigue sensor. Grain № 1: *a*) N = 10 000 cycles; *b*) N = 200 000 cycles.



a *b*

Fig.2. Deformation surface relief of the foil structurally-sensitive fatigue sensor. Grain № 2: a) N = 10 000 cycles; b) N = 200 000 cycles.

It is obvious that the observed difference in the shape and direction of the slip bands is caused by the peculiarities of the crystallographic orientation of crystallites considered.

Previously, during the study of the deformation surface relief of aluminum single crystals and polycrystalline aluminum cladding layer diagnostic parameters that allow to quantify the accumulated fatigue damage have been proposed: a) the density of slip bands [6]; b) the fractal dimension of the deformation relief $D_{p/s}$ [7]; c) damage parameter D, defined by the intensity of the deformation relief.

The comparative analysis of the capabilities and effectiveness of these parameters led to the following conclusions:

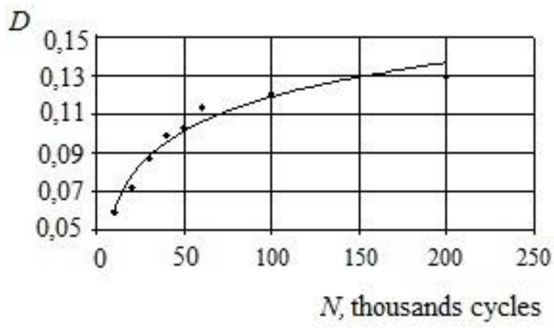
- Density of slip bands can be an effective diagnostic parameter of single crystals and large crystallites only for a certain crystallographic orientation;
- The application of fractal dimensions of the slip bands as a quantitative parameter requires the use of high magnification and resolution of optics;
- Due to the fact that the evolution of slip bands includes increasing the number of lines and bands and their widths, the most effective quantitative parameter of the relief can be a damage parameter *D*, defined as the ratio of the surface area with signs of relief to the overall controlled surface area of the observed spot.

The results of the structurally-sensitive sensors monitoring in the process of cyclical loading

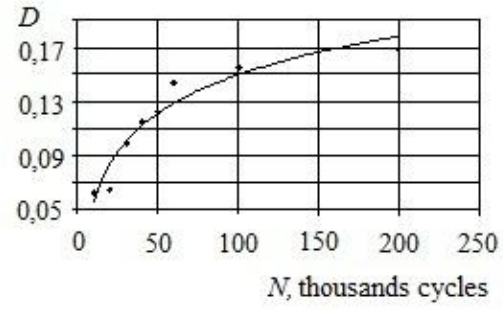
Fig. 3 shows the results of the monitoring of the damage parameter, defined by deformation relief of crystallites № 1 and № 2. For the automated determination of the parameter *D* previously developed equipment and software was used [7].

As it is seen from fig. 3, the dependence of the damage parameter on the number of loading cycles is monotonic throughout the duration of the monitoring period, that confirms the use of the selected parameter as a diagnostic.

Correlation and regression analysis has showed the possibility to use a logarithmic function for description of the relationship between the damage parameter *D* and the number of loading cycles.



a



b

Fig.3. Evolution of the damage parameter *D*:
a) crystallite № 1; *b*) crystallite № 2

Effect of heat treatment on the fatigue characteristics of foil sensors

It is known that the heat treatment of metals change their physical and mechanical properties.

Heat treating of foil sensor is considered as a way to control their sensitivity.

Ability to control sensitivity of sensors means expanding of the range of cyclic loading modes, for which the deformation relief can serve as an indicator of damage.

This, in turn, expands the list of objects for which the foil sensors can be an effective tool for fatigue damage monitoring.

The experiments showed that the heat treatment results in the change of the crystallites size.

In this case, two modes of grain size growth should be considered: a) the grain growth during homogenizing annealing; b) the grain growth as a result of recrystallization. The size of the crystallites and the ability to monitor the deformation relief in the individual crystallites allows considering the structure as quazi single-crystal.

Maximum growth of the damage parameter *D* under cyclical loading was observed on the surface of the foil sensors with quazi single-crystal structure. Thus, the heat treatment may provide certain sensitivity control of sensors.

Prospects of foil fatigue sensors application

Statistics of disasters caused by metal fatigue, shows that monitoring of fatigue damage with foil sensors can be used not only in aviation.

Among the structures, mechanisms and machines that may be a promising application of foil fatigue sensors following examples should be noted: the constructions of ships, railway and motor vehicles, pipelines, bridges, cranes, etc.

Obviously, that an adaptation of the developed tool method of the damage monitoring for various engineering structures requires further research.

Algorithm of such researches should include: a) an analysis of investigated objects loading; b) laboratory testing of structural components with the monitoring of the deformation relief parameters of fatigue sensors installed on components; c) the correlation and regression analysis of the test results for mathematical models of processes that relate the state of the sensors with the number of loading cycles before a critical state of the studied structures elements.

However, taking into account the results of experiments aimed at developing a methodology for fatigue monitoring of aircraft structures [10], this approach can be justified and promising.

Conclusions

In a basis for the concept of the foil fatigue damage sensor lays a proven possibility of the quantitative assessment of fatigue by the surface deformation relief, forming as a result of cyclical loading.

Foil fatigue sensors can be used for the monitoring of service life exhausting of the variety of engineering structures, experiencing fluctuating loads.

For the practical implementation of the method the technique and software have been developed. Basic relationships of relief parameters evolution during the cyclic loading are established.

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