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Surface of Metal as an Indicator of Fatigue Damage

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Abstract:

The possibility of fatigue damage analysis by the extrusion/intrusion structures on the surface of aluminium alloy is shown. Quantitative characteristics of the extrusion/intrusion structures and the methods for their monitoring are substantiated. Two approaches for fatigue analysis are presented: a) direct inspection of the aircraft components, b) application of fatigue sensors.

Keywords:

Aircraft, fatigue, alclad alloy, deformation relief, fatigue sensor, structural health monitoring

1. Introduction

Implementation and expansion of the Damage Tolerance Principle in the aircraft design and operation processes requires development of the appropriate set of non-destructives methods and techniques. Combined altogether these methods form so-called Structural Health Monitoring (SHM) systems. Currently the SHM systems are being under development by Airbus, Boeing and other leading aircraft manufactures [1, 2]. It was proved by numerous investigations that implementation of SHM in practice of aviation can reduce the cost of maintenance up to 30 % due to the shortening of disassembling, inspections, as well as it can decrease stops in operation [3]. For fatigue analysis of the aircraft structures, two approaches are being currently used. The first one is based on the direct diagnostic of the constructional material; second approach is based on the application of fatigue sensors.

Direct diagnostics in SHM can be considered as a branch of conventional Non-Destructive Inspection. That’s why some well-known methods can be used, namely: optical, penetrant, magnetic, ultrasonic, eddy current, radiographic, etc. Each of the

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methods has certain advantages and disadvantages when compared to other methods, so the selection of the appropriate method depends on the type of constructional materials, the scale level of the analysed defects, and inspection cycles.

Simultaneously with the development of direct inspection methods, the different kinds of fatigue sensors have been introduced. Fatigue sensors can reveal accumulated damage by the change of state of sensors attached on or embedded into the structure. If the sensor is made of special highly sensitive material differing from the material of the inspected component, the establishment of the correlation between the property of the component and sensor is required.

After the attempts of many years, some types of sensors have been accepted as effective and promising. These are fibre optics, active ultrasonics, passive acoustic emission, and eddy current sensors.

It is known that as a result of cyclical loading the persistent slip bands, extrusions and intrusions appear and develop on the surface of some metals. From this point of view these are so-called “persistent slip bands” metals.

The analysis of the cyclically deformed single crystal and polycrystalline materials [4-7] has proved the possibility to assess accumulated damage by some parameters of the deformation relief. This phenomenon is a key point of the approach discussed below.

2. Direct Analysis of the Aircraft Components State

Direct analysis of the aircraft components state is based on the analysis of the surface deformation relief. Such relief can be observed on the surface of alclad alloys.

2.1. The 2-D images of the Deformation Relief

The 2-D images of the deformation relief have been obtained on fatigued specimens of the aluminum alloys.

For a skin of civil aircraft, aluminum alloys D16AT and V95 are widely used in the Ukraine and Russia, which are almost analogous to 2024T3 and 7075T6. The main alloying components of D16AT and 2024T3 are copper and magnesium, while V95 and 7075T6 contain about 5 % of zinc. In order to reduce the possible corrosion process, sheets of mentioned alloys are often covered with a layer of pure aluminum (for D16AT and 2024T3) or with a layer of Al with 1.0 % of Zn (for V95 and 7075T6). The thickness of clad layer is ranging from 4 to 7 % of the total sheet thickness.

Aluminum and some of its alloys which may be used for cladding are considered to be persistent slip bands type materials.

Relief intensity depends on the stress level, distribution of the stress near the stress concentrator and the number of cycles.

Flat specimens with a hole in the centre, in order to induce fracture localization were used in a presented fatigue test procedure. Such stress concentrator indicates the point for optical investigation as well. The thickness of the specimen is 1.5 mm and the diameter of the hole is 4.0 mm. These dimensions were chosen because sheets of 1.5 mm thickness are used in many cases for aircraft skin production, where 4 mm hole imitates a constructive hole for rivets. In aircraft structures rivets are used to joint sheets of the skin or mount the skin on frames and stringers. The number of rivets in the structure of a modern passenger airplane for 200 passengers is more than 1.5 million. Thus, such kind of stress concentrator is typical.

Tests have been performed under wide spectrum of loads.

The procedure of accumulated fatigue damage estimation used in the research includes the analysis of digital images of the deformation relief investigated by the light microscope.

For the analysis of the deformation relief, damage parameter D was proposed. It can be calculated as a ratio of the surface with extrusion/intrusion structure to the total analyzed area. Usually the spot of 0.3 mm diameter near the stress concentrator is being analyzed.

The typical curve of the parameter D evolution and corresponding images of the deformation relief under the fatigue is shown in Fig. 1.

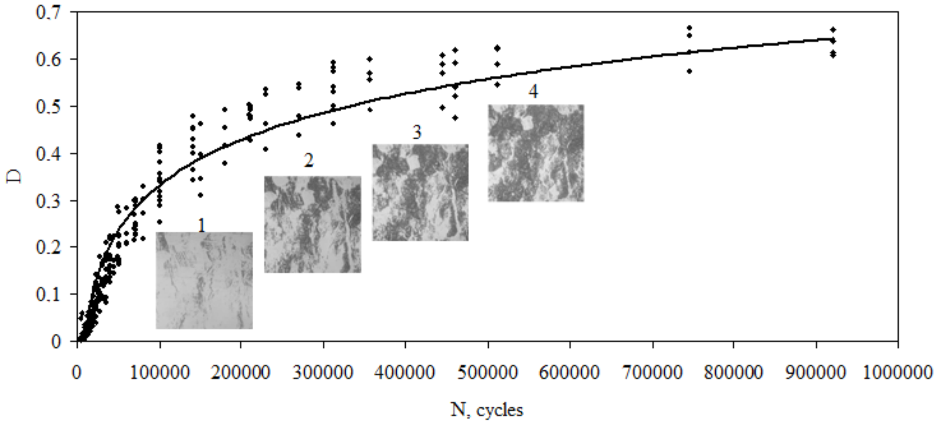


Fig.1 Evolution of the deformation relief under fatigue

Taking into account that the remaining life of the specimen

$$N_{\text{res}} = N_{\text{total}} - N_i \,. \tag{1}$$

where: $N_{\text{total.}}$ is the number of cycles to critical state of the specimen and N_i is the current number of cycles, it is easy to obtain regression models for the prediction of the remaining life of the specimen N_{res}.

For specimens tested at the range of stresses from 70.0 to 120.0 MPa and stress ratio $R = 0$, the following general type of the regression (Fig. 2) has been obtained:

$$\overline{N}_{\text{res}} = 1 - \exp\left(\frac{D-B}{A}\right) \tag{2}$$

where: A, B are empirical coefficients, D is the damage parameter at the N_i.

Thus, it has been proved that there is a possibility to predict remaining number of cycles of the components made of alclad alloys by the 2D images of the deformation relief.

2.2. 3-D Images of the Deformation Relief

The nucleation and evolution of the deformation relief is determined by the evolution of a dislocation substructure and the formation of 3-D extrusion/intrusion slip markings on the specimen surface. Correspondence of the studied structures to the well-known scheme of the extrusion and intrusion formation was proved by the scan microscope investigation.

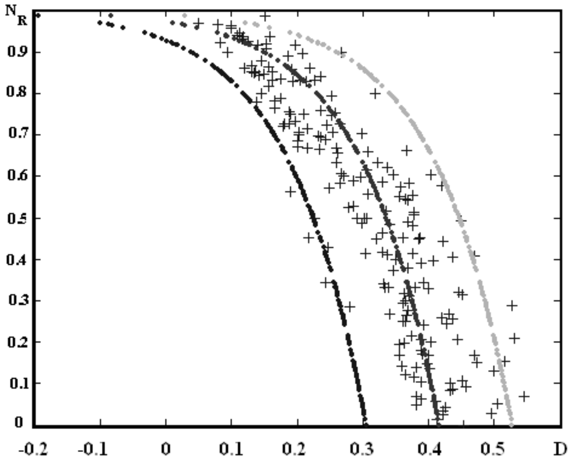


Fig. 2 Relationship between damage parameter D and remaining life of specimens tested at stresses from 70.0 to 120.0 MPa (95% confident interval is shown)

The digital photo of the specimen surface with developed deformation relief obtained by the scan microscope SEM-515 – “Phillips” with the voltage of 30 kV is presented in Fig. 3.

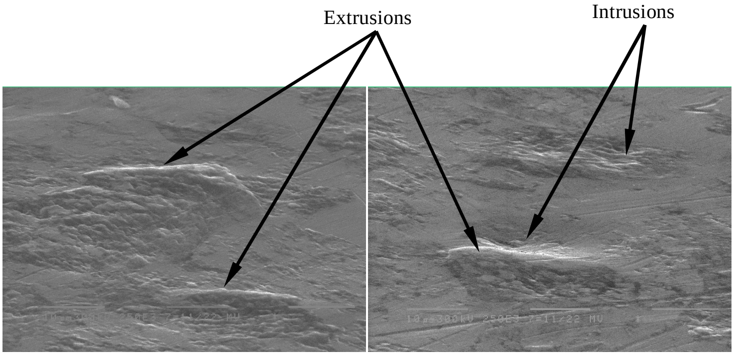


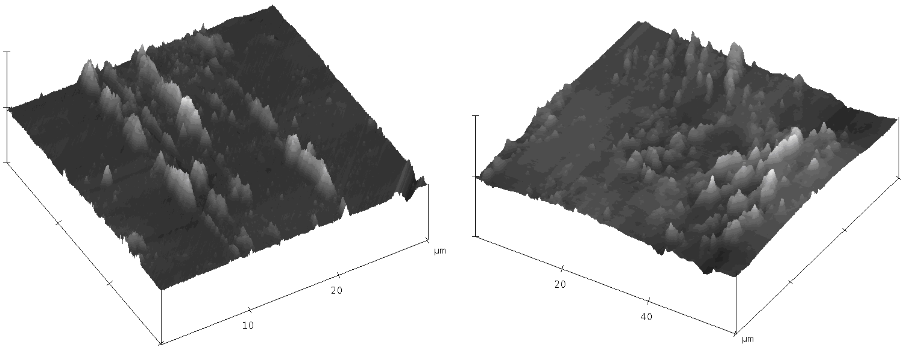
Fig. 3 The surface of the aluminum layer of alclad alloy D16AT investigated by scan microscope SEM-515 (2500 ×)

The presented images of the surface reveal a set of extrusions, intrusions, and persistent slip bands formed under the cyclic loading.

As an additional source of information, the atomic force microscopy may be used. Fig. 4 presents some details of the relief and provides with quantitative parameters at the microscale level.

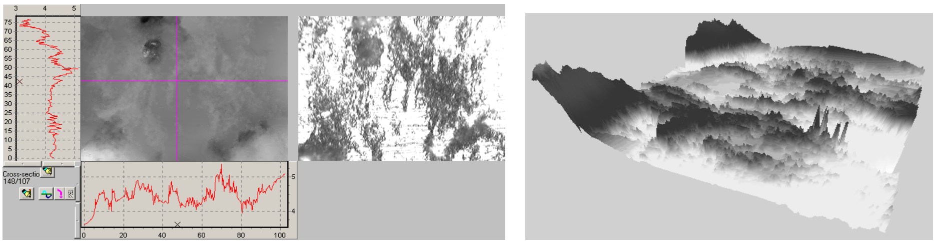
Original equipment has been designed to monitor roughness of the tested specimens [4]. The 3-D profilometer “Micron-alpha” is designed on the base of well known Linnik interferometer. An example of the output data is presented in Fig. 5 and Table 1.

The 3-D methods of the relief investigation presented above open some additional possibilities for the quantitative assessment of the relief and corresponding fatigue damage.



a) b)

Fig. 4 The 3-D images of different kind of deformation relief formation: a) a set of persistence slip bands, b) a combination of coalescence persistence slip bands in two directions



a) b)

Fig. 5 Interface of program for quantitative analysis of deformation relief (a), and 3-D image of the relief obtained with "Micron-Alpha" profiler (b)

Tab. 1 Extrusion/intrusion geometry revealed by "Micron-Alpha" profiler

Maximum stress of cycle [MPa]	Height of the extrusions at the 0.75 mm distance from the stress concentrator [µm]	Depth of intrusions at the 0.75 mm distance from the stress concentrator [µm]
120.2	0.8	0.8
67.3	0.6	0.6

2.3. *Fractal Dimension of the Deformation Relief*

The search for additional criteria for the deformation relief quantitative analysis has led to fractal geometry [7], which is widely used nowadays for solving material science problems. In paper [8] some examples of fractal geometry application for the description of the processes of slip lines initiation and propagation on the single-crystals surface are presented. The deformation relief of aluminum under fatigue can be considered as a self-organized structure; that is why the fractal geometry can be applied to the relief investigation.

The aim of the presented test is to justify experimentally the possibility of quantitative estimation of accumulated fatigue damage by the 2-D parameters and fractal dimensions of deformation relief which is being formed under fatigue on the alclad alloys surface.

Specimens of aluminum alloys D16AT, 2024T3 and 7075T6 have been loaded by bending with the wide range of stresses at the frequency of 25 Hz. The surface was polished with diamond paste.

Nowadays there are a lot of methods of the fractal dimensions calculation for the natural objects. One of the most widespread is a “box counting” [8]. This method allows calculating the definite types of fractal dimension.

The first possible type of fractal dimension is fractal dimension of the boundaries of deformation relief spots. This type of fractal dimension is designated as *Dp*.

For some fractals the most informative parameter is the fractal dimension of the ratio of perimeter to area. It is known that this ratio characterizes the shape of objects, and for the regular geometrical figures this parameter is a constant value and does not depend on the object size.

Corresponding fractal dimension for the clusters of deformation relief will be further called *Dp/s*.

For the data processing automation the special software has been developed.

Fractal dimensions of the deformation relief clusters contours as well as the fractal dimensions determined by the ratio of perimeter to area exceed topological dimension of the line and are within the range of 1 to 2.

Damage parameter *D* and fractal dimension *Dp/s* were selected as the main diagnostic parameters.

Here we consider evolution of damage parameter *D* and fractal dimension *Dp/s* during loading process of series specimens, tested under the maximum cycle stress of 173 MPa and minimum cycle stress of 0 MPa.

The practical task of the accumulated fatigue damage monitoring is a prediction of the residual life of the aircraft structure components. In Fig. 6 the relationships between the damage parameter *D* and fractal dimension *Dp/s* with residual numbers of cycles are shown. As it is seen from the presented graphs both parameters correlate with the accumulated fatigue damage.

In this relationship damage parameter *D* points on saturation of the surface with the extrusions and intrusions that form deformation relief while the changing of the fractal dimension *Dp/s* characterizes the process of the deformation relief clusters coalescence.

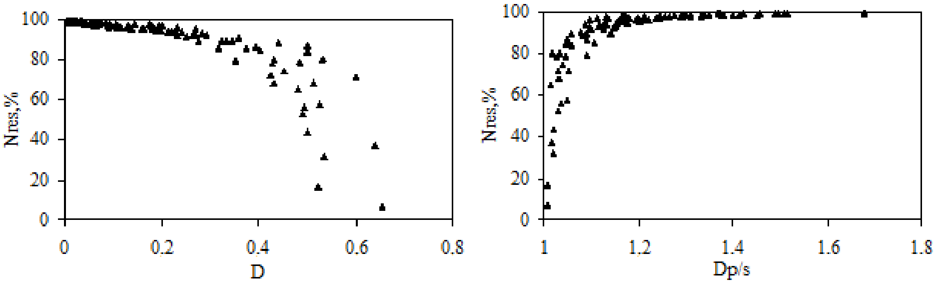


Fig. 6 Relationship between residual life and damage parameter D and fractal dimension Dp/s

The observed increase of data scattering is determined by attaining the saturation stage when the residual life approaches zero. It means that after attaining a certain critical level of damage parameters there is no further growth of deformation relief with increase of the number of cycles.

As it can be seen from Fig. 6, parameters D and Dp/s complement each other. That's why multiple regression models must be used for residual life prediction.

Dispersion and regression analysis has shown the possibility of the multiple correlation model application:

$$N_{\mathrm{res}} = 180.346 - 109.588D - 56.6685 Dp/s \quad (\%)\,, \tag{3}$$

where D is the damage parameter, Dp/s is the fractal dimension, N_{res} (%) is the residual number of cycles.

Analysis performed proves the significance of both considered models parameters: damage parameter D and fractal dimension Dp/s.

3. Structurally sensitive fatigue indicators for analysis of aircraft components state

Structurally sensitive fatigue indicators are based on the same key idea: deformation relief indicates accumulated fatigue damage. Several types of the fatigue indicators have been developed [9], among them the sensor made of alclad aluminum alloy D16AT seems to be most appropriate for the aircraft fatigue monitoring.

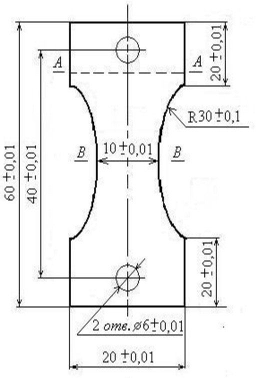


Fig. 7 Fatigue sensor

Fatigue sensor looks like a micro specimen for fatigue test (Fig. 7). The neck in the working section of the sensor provides local increase of the stress according to the necessary sensitivity.

The experience of the previous applications of the fatigue damage specimen-witness in aviation was used for the definition of the place and method of the indicator installation. The specimen-witness on airplanes can be placed at the rear wing spar of the wing (Fig. 8).

The quality of the sensor surface is reached by the mechanical and electrolytic polishing. It is necessary for the light microscopic analysis of deformation relief, which is formed on the surface of sensor. It was shown above that the deformation relief can be described by some 2-D, 3-D and fractal parameters. The analysis has shown that most appropriate parameters are damage parameter D and 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 sensor's residual life prediction in the general view:

$$N_{\text{res}} = A + B \log D + C \log Dp/s \ . \qquad (4)$$

where N_{res} is the number of cycles to the fracture, *A*, *B*, *C* are constants, *D* is the damage parameter and *Dp/s* is the fractal dimension.

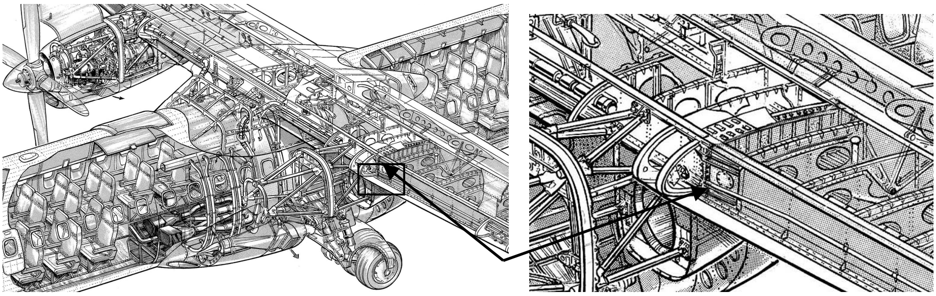


Fig. 8 Aircraft spot where the sensor could be attached

The test conducted under different loading conditions has shown that the accuracy of corresponding multiple regression model can be expressed by the coefficient of determination R^2 in the range from 0.75 to 0.95. Of course an additional test for the estimation of the correlation between the sensor and aircraft components is necessary. The program for the sensor adoption depends on the loading condition, expected service life, and other factors.

4. Conclusion

The process of the fatigue damage accumulation in alclad aluminum alloys is associated with origin and evolution of the surface deformation relief. The intensity of the relief indicates the exhausting of the bearing capacity of the structural components. If the component made of the metal which does not reveal extrusion/intrusion structures, the appropriate way to monitor fatigue is an application of fatigue sensors.

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