Computer Aided Optical Method for Aircraft's Components Fatigue Life Estimation

Sergey Ignatovich[1,a], Michail Karuskevich[2,b] and Tatijana Maslak[3,c]

National Aviation University, Komarov ave.1, 03058, Kyiv, Ukraine

[a]ignatovich@nau.edu.ua, [b]mkaruskevich@hotmail.com, [c]mtina@bigmir.net

Keywords: alclad constructional alloys, fatigue, deformation relief, evolution of the fractal dimension

The results of numerous tests show that quantitative estimation of accumulated fatigue damage may effectively be conducted by computer-aided optical analysis of the surface state. The method can be applied for alclad aluminium alloys which are used for modern aircraft skin manufacturing. The developed optical system and its software allow to determine the density of the areas with slip bands (damage parameter D), and a set of surface pattern fractal dimensions. These parameters allow to indicate more dangerous points of aircraft structures, predict fatigue crack under full scale test of aircraft structures as well as estimate residual service life.

Introduction

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

Full tests are an inherent part of strength and life support which are permit to determine aircraft's construction weak points and their vitality. The reliable instrumental diagnostic at the early stage of fatigue damage allows to reduce tests duration and their cost.

These methods may also be used during the maintenance operations. The use of these methods are necessary because the loading conditions for aircraft vary and as a result the process of aircraft life exhausting is not the same for different aircrafts.

Direct inspection may be performed by applying non-destructive methods, such as acoustic emission test, high frequency ultra sonic, penetration, eddy current test methods, etc.

The variety of construction materials, loading conditions, requirements to the sensitivity of diagnostic methods determine the necessity of creation the many methods for quantitative determination of the accumulated damage and prediction of residual life.

Our investigations show that such quantitative estimation may effectively be conducted by computer-aided optical analysis of the surface state.

This approach can be realized: a) by the analysis of the state of so-called specimen-witness or sensors, which are attached to the structure in the area of the considerable stress and carries operational spectra of loads, change their parameters and in such way give information about fatigue damage accumulated in components; b) by the direct check of aircraft component state.

In the paper [1] the single-crystal sensor of deformation damage has been used. In this case the diagnostic parameter is the slip lines density on the sensor surface. The sensor is a plate of 20x10x0.2 mm polished on one side bonded by the glue to the aircraft component.

Estimation of the slip lines number is conducted by the light microscope.

Carried out researches point on close correlation dependence of slip lines density with number of cycles to failure and with a level of applied loads.

It isn't necessary to use the single-crystal sensor for some kinds of materials because deformation relief is formed directly on their surface. Typical materials of such category are alclad aluminium alloys.

In the paper [2] quantitative damage parameter D was proposed. The value of this parameter is determined as a ratio of surface area with signs of microplastic deformation to the total area of the surface observed.

During the test the surface area of 0.3x0.3 mm just near the stress concentrator (hole) is explored.

In papers [3-6] the method of automatic estimation of damage parameter D and distribution of damage parameter near the stress concentrator, as well as results of damage parameter monitoring under fatigue are presented, the possibility of aircraft structural components residual life is proved.

The search of the additional criteria for deformation relief at quantitative description leads to fractal geometry which is widly used nowadays at solving the material science problems.

So, in paper [7] some examples of fractal geometry application for the description of the processes of slip lines initiation and propagation on the surface of single crystals are presented.

Evolution of surface fractal dimension under the deformation of titanium plate has been investigated in the paper [8].

The fall of fractal dimension has been observed while the essential signs of strain on the scan-microscope images were absent.

It was shown that fluctuations of fractal dimension are maximum during the process with dominant mode of deformation.

Analysis of deformation processes results in application of fractal geometry which allows to choose approaches that improve 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.

The aim of presented paper is to justify experimentally the possibility of quantitative estimation of accumulated fatigue damage by the saturation parameters and fractal dimensions of deformation relief, that is forming on the surface of alclad constructional aluminium alloys under fatigue.

Experimental procedure

Aluminium alloys D16AT, 2024T3 and 7075T6 have been chosen for experiment. These materials are widely used to manufacture modern aircraft skin in Ukrainian, Russian and Western aircraft industry.

Specimens have been loaded with the wide range of stresses at frequency 25 Hz. The surface was polished with diamond paste.

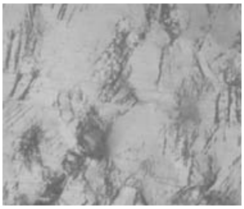
As a result of cyclic loading the deformation relief is originated and developed. Intensity of the relief depends on the stress level, distribution of the stress near the stress concentrator and number of cycles. The procedure for accumulated fatigue damage estimation used in the research includes the application of digital images (fig.2,a) of the deformation relief observed by the light microscope.

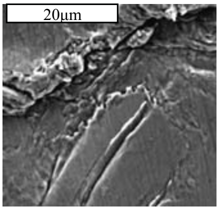
Correspondence of the studied structures to the well-known scheme of the extrusion and intrusion formation [9] was proved by the scan microscope investigation of aluminium specimens at the wide range of the loading modes.

In fig.2, b the digital photo of the specimen surface with developed deformation relief obtained by the scan microscope SEM-515 – "Phillips" with the voltage 30 kV is presented.

In the papers [3-6] processing of digital images of alclad aluminium alloys surface that allows quantitative estimation of the level of the surface saturation with the microplastic deformation signs and correspondent accumulated fatigue damage were shown.

As the presented data has shown, the fractal dimension of deformation relief describes the shape of relief clusters and could be considered as an additional damage parameter that significantly improves the accuracy of the accumulated fatigue damage estimation.





a) b)

Fig. 2. The surface of aluminium layer of alclad aluminium alloy D16AT: a) light microscope (x 500), b) scan microscope SEM-515.

Nowadays there are a lot of methods for the fractal dimensions calculation for the nature objects. One of the more widespread is a “box counting” [7].

The method gives the possibility to calculate fractal dimension of the relief cluster boundaries. Fractal dimension of the cluster boundaries designated as $D_{p.}$

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

In the paper [10] such kind of dimension describes the shape of clouds and reins.

Correspondent fractal dimension for the clusters of deformation relief will be further called $D_{p/s}$.

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

Main stages of calculations are: transformation of digital images of a surface into the monochromic; separation of single clusters of deformation relief; determination of the deformation relief clusters contours; overlapping of the box net on the cluster`s contours or on their surface; calculation of the box number, overlapping contours of clusters or their surfaces; graphs construction of the relationships $\ln N_p=f(\ln(1/b))$; $\ln N_s=f(\ln(1/b))$ and $\ln N_p=f(\ln(N_s))$, where N_p – number of cells (boxes), overlapping contours of deformation relief clusters; N_s – number of cells overlapping surface of deformation relief clusters; b – the size of the cell.

Typical graph of the relationship $\ln N_p = f(\ln(N_s))$, obtained during the presented research is in fig. 3.

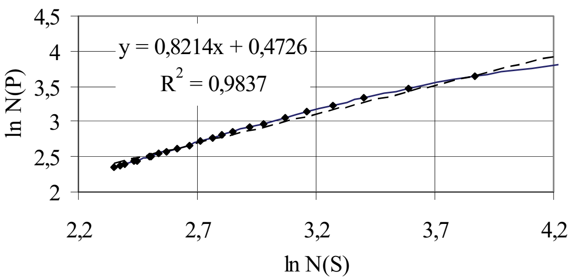


Fig. 3. The relationship between number of cells overlapping clusters contours and number of cells overlapping area of clusters.

Fractal dimension $D_{p/s}$ with the application of geometrical method was estimating as a doubled absolute value of the tangent of the slope angle of the middle part of the fractal graph in its linear approximation in log-log coordinates [11].

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.

Experimental results

The design of specially constructed test machine allows to carry out optical observation of the specimen surface after initial several cycles of loading (fig.1). Damage parameter D and fractal dimension $D_{p/s}$ are diagnostic parameters.

Here we consider evolution of damage parameter D and fractal dimension $D_{p/s}$ during the process of one specimen loading, tested under the maximum cycle stress 235,5 MPa.

The practical task of the accumulated fatigue damage monitoring is a forecast of the residual life of the aircraft structure components.

In fig. 4 and fig. 5 the relationship of the damage parameter D and fractal dimension $D_{p/s}$ with residual number of cycles is shown.

As it is seen from the presented graphs, both parameters point to the accumulated fatigue damage.

In this relationship damage parameter D points to saturation change of the surface with the extrusions and intrusions that form deformation relief, while changing of the fractal dimension $D_{p/s}$ characterizes the process of the deformation relief clusters coalescence.

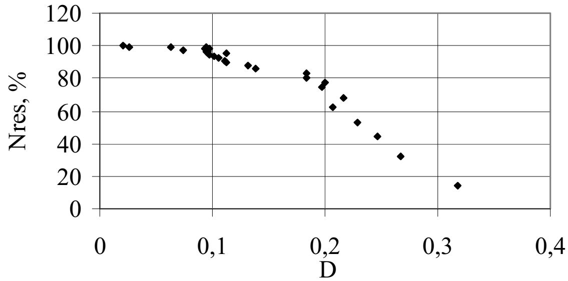


Fig. 4. Relationship between residual life and damage parameter D.

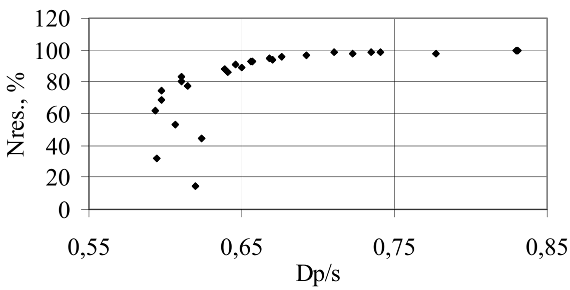


Fig. 5. Relationship between residual life and fractal dimension $D_{p/s}$.

In this connection we can apply multiple correlation models in the life forecast process. In such way both parameters of the deformation relief should be taken into account.

Dispersion and regression analysis made with module "ANOVA" of the "Statgraphics Plus" has shown the possibility of the multiple correlation model application:

$$N_{res.},\%=228,252 - 385,169\ D - 69,067\ D_{p/s},$$

where: D – value of the damage parameter; $D_{p/s}$ – fractal dimension; $N_{res.,\%}$ - residual number of cycles, %.

Correspondent value of the R^2 equals 92,2851 %. Standard error is 6,48.

Analysis performed proves the significance of both considered models parameters: damage parameter D and fractal dimension $D_{p/s.}$

As a result of scheduled researches, the following exemplary procedure for aircraft fatigue analysis might be proposed:

1. Operating range of loads, load distribution along the structure, and material characteristics are determined. According to recommendations of International Civil Aviation Organization (Doc. 9051-AN/896, ICAO, 1987) the load range must be based on statistic tests data obtained by generalized load researches for the particular airplane type, in case of insufficient data - with the help of supposed use of aircraft.
2. Structure parts to be investigated are determined. The location of a possible damage can be determined by analysis or on the basis of endurance tests of the whole structure or its separate elements.
3. Laboratory fatigue tests of structure elements (specimens) are carried out to create data bank. Critical area, that is an area responsible for destruction, is polished for microscopic investigation. Photographing of critical area is performed by a metallographic microscope equipped with a digital camera.

The data bank (atlas) must contain test results on different load levels, different sequences of load application, etc. For each state the factor of service life is calculated as a ratio of the number of cycles corresponding to a given state to cycle number to failure under given loading condition.

4. Monitoring of fatigue process of aviation structures under full-scale test is performed by means of inspection of skin clad coating in areas determined in accordance with requirements of item 2 and by technology stated in item 3.
5. The analysis of an inspected part of a structure is conducted by estimation of damage parameter D and fractal dimensions and calculation of the residual fatigue life by the use of multiple regression models.

Besides presented above computer aided optical method of the surface images analysis, the surface state can be studied and quantitatively estimated by the interference profilometer developed in the National Aviation University. Profilograms obtained not only give parameters of roughness, but could be used for the surface dimension estimation.

Conclusion

The presented results indicate the possibility of the accumulated fatigue damage estimation as well as possibility of the residual life forecast for aircraft structure components, made of alclad aluminium alloys by using the computer aided optical method of the surface deformation relief analysis.

For the structure components residual life prediction, multiple correlation models, including damage parameter D, that characterizes saturation of the surface with the signs of micro plastic deformation, and fractal dimension $D_{p/s}$ determined by the ratio of the deformation relief clusters perimeter to their area can be used.

References

[1] Zasimchuk E.E., RadchenkoA.I., Karuskevich M.V. Single-crystals as an Indicator of Fatigue Damage // Fatigue Fract. Engng. Mater. Struct. - 1992. - Vol. 15, N 12. - p. 1281-1283.

[2] Ignatovich S.R., Karuskevich M.V., Karuskevich O.M. UK. Patent 3470 (2004)

[3] Karuskevich M.V., Ignatovich S.R., Karuskevich O.M., Panteleev V.M. Fatigue diagnostic of alclad aluminium alloy // Vestnik NTTU KPI. Mashinostroenie. – 2002. – № 43. – pp. 53 – 55 (in Russion).

[4] Karuskevich M.V., Ignatovich S.R., Karuskevich O.M., Hizhnjak S.B., YakushenkoO.S. Fatigue monitoring of constructional aluminium alloy // Visnik NAU. – 2004. – № 1(19). – P. 88 – 91 (in Ukrainian).

[5] Karuskevich M.V., Ignatovich S.R., Karuskevich O.M., Evolution of alloy D-16AT damage near the stress concentrator at the initial stage of fatigue// Journal of the National Aerospace University – 2004. – № 4(12). – P. 29 – 32 (in Ukrainian).

[6] Karuskevich O.M. Influence of the stress level on deformation relief development // Vestnik dvigatelestroenija. – 2005. – № 2. – P. 79 – 83.

[7] Ivanova V.S., Balankin A.S., Bunin I.Zh.: *Synergetic and fractals in the material science* (Nauka, Moskov 1994).

[8] Kulkov S.N., Mironov Yu.P., Fractal dimension of the surface under martensite deformation transformation in the nickelid of the titanium, Journal of the technical physics. – 2004. – V.74. – Issue 4. – P. 129-132.

[9] Goritskiy V.M., Terentiev V.F. *Structure and fatigue fracture of metals* (Metalurgija, Moscov 1986).

[10] Feder J.*Fractals* (Mir, Moscov 1991).

[11] Lovejoy, S. Area-perimeter relation for rain and cloud areas. Science, 216, 185 – 187, 1982.