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FATIGUE FAILURE PREDICTION FOR FUSELAGE SKIN MADE OF ALCLAD ALUMINIUM ALLOY

M. Karuskevich, D. of Engineering

National Aviation University

mkaruskevich@hotmail.com

The basis for the empirical-analytical method for the estimation of the fatigue crack propagation duration in alclad aluminium alloys is presented in the paper. The method is based on the usage of the regression equations, establishing the relationship between fatigue crack kinetic and damage accumulated near the stress concentrator. As characteristics of the local damage the quantitative parameters of the deformation relief are used. Analysis of the deformation relief is conducted by the computer aided optical method.

Keywords: damage tolerance, fatigue crack, deformation relief.

Подано основи експериментально-аналітичного методу визначення тривалості стадії розповсюдження втомних тріщин у плакованих алюмінієвих сплавах. Метод ґрунтується на використанні регресійних рівнянь, які встановлюють зв'язок кінетики втомних тріщин з накопиченим у концентратору напружень втомним пошкодженням. В якості характеристики локального пошкодження використовуються кількісні характеристики деформаційного рельєфу. Аналіз деформаційного рельєфу виконується компьютерізованим оптичним методом.

Ключові слова: допустиме пошкодження, втомна тріщина, деформаційний рельєф.

Introduction

In the last few decades the Damage Tolerance principle has become widely used in civil aviation. The Damage Tolerance principle presumes operation of the aircraft with defects of the safe size. One kind of the mentioned damage is a fatigue crack of defined length. The necessity of fatigue crack propagation is apparent. At the same time the duration of the crack propagation from the length of reliable indication to the critical size must be no less than two times greater of the interval between inspections of the structure. The structure with fatigue crack must maintain bearing capacity under one time applied maximum operational load.

As a rule, the rate of fatigue cracks propagation determined according to the principles of fracture mechanics [1], nevertheless, as it was shown by the conducted tests, prediction of the alclad aluminium alloys fracture may be performed on the basis of the analysis of local accumulated damage.

Assessment of the local damage may be conducted by the parameters of the surface deformation relief forming nearby stress concentrators.

Fatigue cracks in aircraft structures

In spite of significant progress achieved in last years in the field of the providing the strength and lifespan of aircraft structures, fatigue cracks remain to be common flow that can be revealed at the diagnostic of the aircraft technical state. So, for example at the paper [2] presented data of defects found on the Tu-154 and Il-86 planes, which are in operation in Russian Federation. In the table 1 the data related to the Il-86 are presented (see table). The data confirms that the fatigue as well as corrosion and wear are the spread kind of the damage of fuselage, wing and empennage of an aircraft. Investigations of the aircraft fatigue have become wide scale after the crash of two Comet planes in 1954 caused by fatigue. Nevertheless the disasters in following years were not prevented.

The following disasters should be mentioned here: the crash of Boeing 707 after the 47621 hours and only 16724 flights (1977, fatigue failure of the horizontal stabilizer), the failure of the upper section of the fuselage skin of the Boeing 737 (1988) after 89680 cycles “take off-landing”, the crash of the Boeing 747SR plane in 1985 (fracture of the pressure bulkhead) [3].

There are also fatigue failures of the planes in the USSR, for example the crash of An-10 in 1972 caused by the fracture of the wing lower panel [4].

Taking into account scientific, economical and social aspects of the aircraft fatigue problems, one can claim that researches directed on the development of methods for the fatigue and fracture processes prediction remains actual.

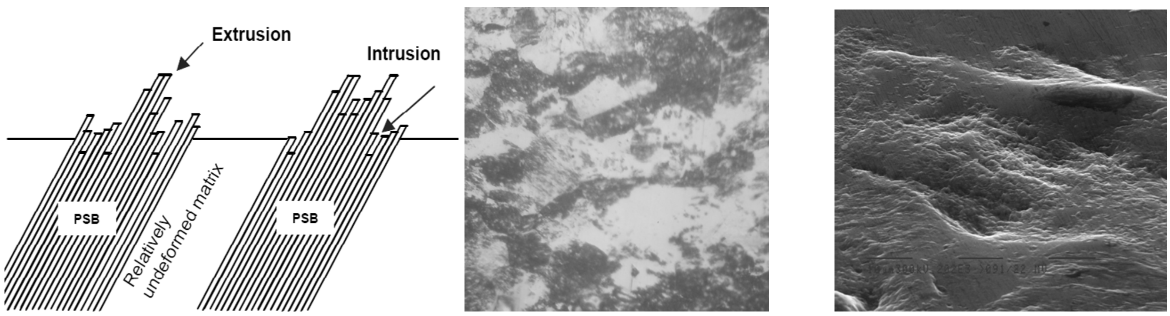
Deformation relief as an indicator of accumulated fatigue damage

Despite the widely practiced use of composite materials, the skin of the majority of modern planes made of alclad aluminium alloy.

Cladding of the alloys D16AT, 2024T3 is performed by pure technical aluminium. The thickness of the clad layer approximately equal to 4 % of the sheet thickness. Nucleation stage of alclad aluminium alloy fatigue associated with formation and development of the surface deformation relief, which is actually a set of the extrusions, intrusions, and persistent slip bands (fig. 1).

Operational damages of the Il-86 airframe [2]

Aircraft part	Type of damage									
	Corrosion		Fatigue		Wear		Mechanical damage		Total, damages	
	Number	%	Number	%	Number	%	Number	%	Number	%
Entire structure	53	60,92	15	17,24	14	16,09	5	5,75	87	100
Fuselage	52	73,24	13	18,31	4	5,63	2	2,82	71	81,61
Wing	–	–	2	16,67	8	66,67	2	16,67	12	13,79
Empennage	1	33,33	–	–	1	33,33	1	33,33	3	3,45
Landing gear	–	–	–	–	1	100	–	–	1	1,15



a *b* *c*

Fig. 1. Deformation relief of the surface of the alclad layer:
a — scheme of the deformation relief formation; *b* — optical image; *в* — scan electron-microscopy image

Deformation relief can be observed by the application of light microscope. The quantitative analysis of the accumulated damage may be conducted by the analysis of the digital photos, obtained with magnification 200^x–400^x.

For the quantitative assessment of deformation relief it was proposed to use a set of original parameters: the damage parameter D, which characterizes intensity of the relief; fractal dimension of the deformation relief clusters $D_{p/s}$, which is characteristic of the shape of deformation relief clusters [5–7]. Damage parameter D calculated as a ratio of the surface area with signs of micro plastic deformation to the total investigated surface area.

Special computer aided optical equipment and software have been developed for automated estimation of the damage parameter.

The relationship between values of proposed parameter and damage accumulated at the nucleation stage of fatigue has been established.

The feature of the evolution of the intensity of deformation relief in the process of cyclical loading allows to consider damage parameter D as a main characteristic of the relief and correspondent damage.

In the fig. 2 the graph of the deformation relief evolution is shown.

The relationship has been obtained by the test with regime of loading closed to operational.

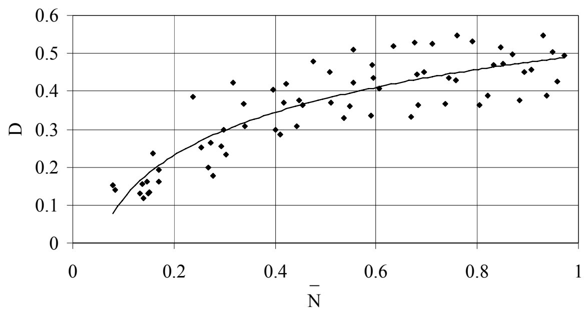


Fig. 2. Evolution of the damage parameter D in the process of cyclical loading, σ_{max} = 120,2 MPa.

Relative cyclical loading, $\bar{N}$ determined as a ratio of current number of cycles of loading to the number of cycles corresponded to the achievement of the critical state of the specimen. As a critical state of the specimen the achievement of the crack size 1,0 mm was accepted.

Critical damage parameter

As it is seen from the fig. 2, where the evolution of the deformation relief intensity near the stress concentrator at the nucleation stage of fatigue is presented, the certain range of the damage parameter D, corresponded to the crack initiation exists.

Thus, the fatigue crack can start on the base of different deformation damage. This determines certain difference of the local state of material of investigated specimen.

To denote damage parameter D, corresponded to the origin of the fatigue crack, it is proposed to use term "critical damage parameter", $D_{cr.}$

Taking into account that the area of the damage localization and forming of the deformation relief under the defined regimes of loading is only few millimeters of diameter, the correlation between critical damage parameter and characteristics of the crack propagation process may be presumed.

Methods and experimental results

Conducted experiments were directed on the acceptance of the data about the propagation of fatigue cracks in the specimens of sheets of the alclad alloy D16AT and on the establishment of the correlation link between duration of the crack propagation and damage accumulated at nucleation stage of fatigue.

The sketch of the specimen with side notch and the geometry is shown in fig. 3.

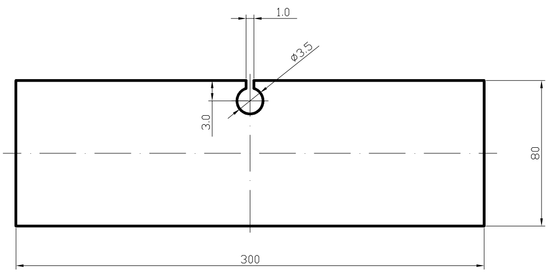


Fig. 3. The specimen for fatigue test

Fatigue tests were conducted on standard hydro-pulsating machine with axial tension and maximum stress of the cycle 60,0; 70,0; 80,0 MPa and stress ratio $R = 0$.

The selection of the regimes of loading is based on the requirement to close the test regime to the loading conditions of real aviation structures.

At the process of test the following parameters were registered: the value of damage parameter near the stress concentrator and corresponded number of cycles at the nucleation stage of damage; the moment of the formation the crack of 1,0 mm length; the length of the crack and correspondent number of cycles at the stage of crack propagation; the number of cycles to the specimen failure.

At the conducted experiments the critical value of damage parameter $D_{cr.}$ determined, i.e. the value of the parameter corresponded to the achievement of the relief saturation stage and forming of the fatigue crack. It was proposed and then experimentally proved that after the fatigue crack appearance the intensity of deformation relief near the stress concentrator do not change.

In the fig. 4 as an example the dependence of the duration of the fatigue crack propagation N_{crack} expressed in thousands of cycles of loading on the critical damage parameter $D_{cr.}$ obtained in the result of the test with maximum stress of the cycle 70,0 MPa with stress ratio $R = 0$.

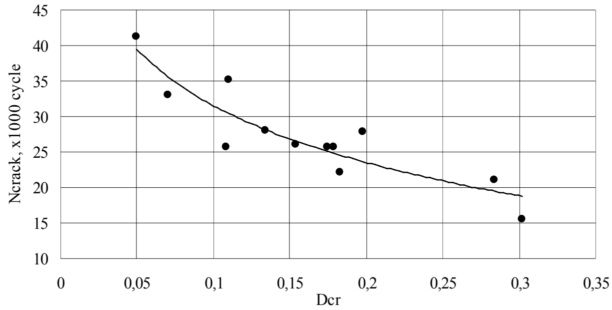


Fig. 4. The relationship between duration of the crack propagation stage and critical damage parameter

Similar view have relationships, obtained in the tests with maximum stress of the cycle 60,0 MPa; 80,0 MPa. Obtained regression relationships have general form:

$$N_{crack} = A - BLn(D_{cr}).$$

In the fig. 5 the dependence of the crack propagation rate at the initial path, which size is 4,0 mm, on the critical damage parameter. The graph approves close relationship between the local damage and parameters of crack growth.

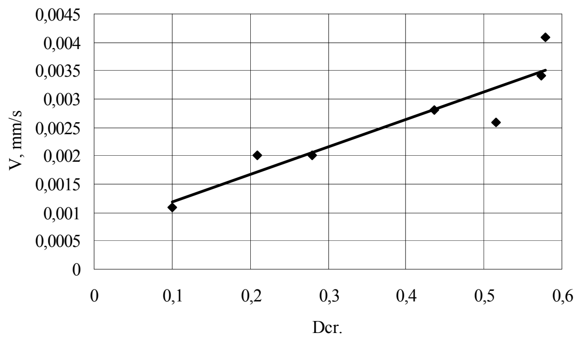


Fig. 5. The relationship between the rate of the crack propagation and critical damage parameter

The size of mentioned area, where the relationship was obtained correspondents to the area of the developed deformation relief formed to the moment of crack initiation.

The relationship between intensity of deformation relief and fatigue crack rate remains also at the propagation beyond the boundaries of indicated area, but the density of the correlation between the values of critical damage parameter and rate of propagation weakens (fig. 6).

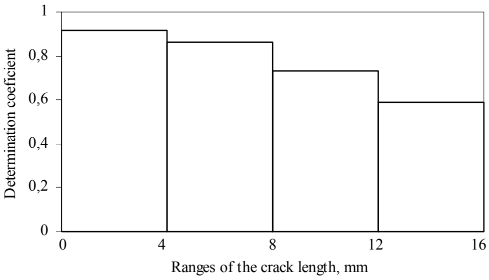


Fig. 6. Coefficients of determination R^2 of the dependence of crack propagation rate on critical damage parameter $D_{cr.}$ obtained for cracks in the ranges: *а* — 0–4,0 mm; *б* — 4,0–8,0 mm; *в* — 8,0–12,0 mm; *г* — 12,0–16,0 mm

Prediction of the crack propagation in structural components

Possibility to predict durability of fatigue crack propagation by the deformation relief near the stress concentrators has been proved by test of aircraft structural components, i.e. specimens which are models of the joints of the skin with stringer.

The scheme of the specimen presented in the fig. 7.

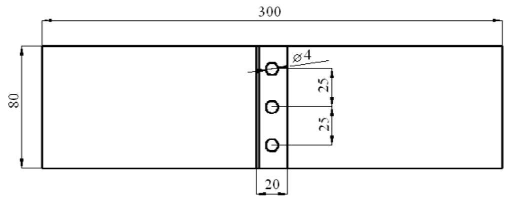


Fig. 7. Specimen of the rivet joint of skin with a stringer

The test were conducted with maximum stress of the cycle 100,0 MPa and stress ratio $R = 0$. On the plot (fig. 8) the dependence of the duration of the crack propagation in rivet structural component on maximum intensity of deformation relief near the hole for rivet.

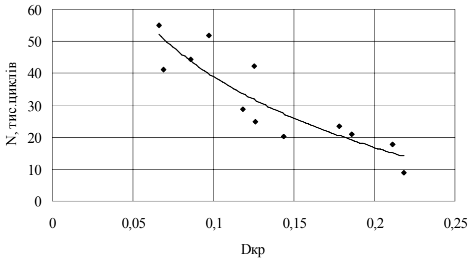


Fig. 8. The relationship between the duration of crack propagation stage and critical value of damage parameter near the stress concentrator-hole for rivet

As well as under the test of the flat specimen with side notch, the presented relationship may be described by logarithmic function.

The density of the correlation between the duration of the fatigue crack propagation and critical value of the damage parameter D characterized by rather high value of the determination coefficient $R^2 = 0{,}78$.

Conclusion

Assessment of the rate and duration of the fatigue crack propagation in the sheet alclad aluminium alloys can be conducted by the surface deformation relief near stress concentrators. Method has been approved by the fatigue test of structural components, which are models of the skin of modern regional plane.

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