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INFLUENCE OF ACCUMULATED FATIGUE DAMAGE ON CRACK PROPAGATION IN ALCLAD ALUMINUM ALLOY

***M. V. Karuskevich*[1], *S. V. Shchepak*[1], *O. I. Shchur*[1], *A. V. Plashchinskaya*[2]**

[1]National aviation university,

[2]Institute of mechanics named after S. P. Tymoshenko of NAS of Ukraine

mkaruskevich@hotmail.com

Використання концепції допустимого пошкодження при експлуатації повітряних суден припускає можливість прогнозування розповсюдження втомних тріщин. Проведенні дослідження доказали, що накопичена в наслідку циклічного навантаження локальна пошкоджуваність металу оказує вплив на розвиток втомних тріщин, особливо на начальній стадії. В якості показника пошкодження використовується насиченість деформаційного рельєфу біля концентратору напружень. Встановлено кореляційний зв'язок між продовженням розповсюдження тріщини і насиченістю деформаційного рельєфу біля концентратора напружень.

Ключові слова: авіаційні конструкції, втомні тріщини, алюмінієві сплави, деформаційний рельєф, накопичення пошкодження.

Application of damage tolerance principle at operation of aircrafts assumes ability to predict propagation of fatigue cracks. Conducted experiments have proved that local metal damage accumulated due to cyclic loadings has influence on fatigue crack propagation, especially on the initial stages of crack development. Density of deformation relief at the stress concentrator is being used as damage indicator. It has been proved, that there exists correlation between time of crack propagation and saturation of deformation relief at the stress concentrator.

Keywords: aircraft structures, fatigue cracks, aluminium alloys, deformation relief, damage accumulation.

Introduction

Ensuring of effective and safe operation of aircrafts is based on the three principles of their design: Safe-Life, Fail-Safe and Damage Tolerance. The abovementioned methods do not contradict each other, but instead complement each other because of the fact that they are being applied to different aggregates, assemblies and parts of the structure. For thin-walled aircraft structures like fuselage, application of damage tolerance approach is most appropriate. In this case a clear need to develop a technique for reliable monitoring of fatigue cracks and prediction of their further propagation arises.

Linear fracture mechanics makes it possible to forecast fatigue crack kinetics by the means of empirical relationships developed by Paris and Erdogan [1], bounding speed of crack propagation with range of the stress concentration coefficient as

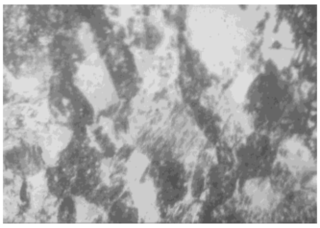
$$\frac{dl}{dn} = C(\Delta K)^q .$$

Such approach does not take into account damage accumulated at the incubatory stage and possible differences of physical and mechanical characteristics of material at the moment of crack initiation.

In this article results of research, which has proved the possibility of fatigue crack propagation prediction based on correlation between deformational relief at the stress concentrator and rate of crack propagation, are being considered.

Deformational relief as an indicator of accumulated fatigue damage

Initial stage of alclad aluminum alloys fatigue is accompanied by formation and development of surface deformational relief, which consists of a set of extrusions, intrusions and slip bands (Fig. 1).



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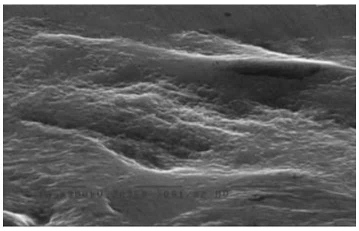

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Fig. 1. Optical (*a*) and electron microscopy (*b*) pictures of aluminum alloy D16AT cladding layer deformational relief

It is possible to observe deformational relief by application of light microscope while assessing it quantitatively by means of digital pictures obtained at 200^x—400^x scale. In order to assess intensity of deformational relief a set of parameters have been

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introduced: damage parameter *D*, which characterizes its saturation, fractal dimensionality of clusters $D_{p/s}$, representing the shape of deformational relief clusters [2–4].

Damage parameter *D* is determined as ratio of area with signs of microplastic deformation to the total area of the controlled area. Special computer aided optical equipment and software for automatic determination of damage parameter has been developed.

Existence of correlation between value of the introduced parameter and amount of damage accumulated at the incubatory stage of fatigue has been proved.

Results of the experiments

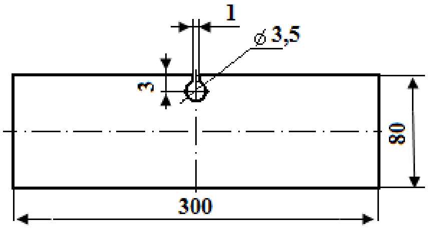
The performed experiments were aimed at obtaining data about development of fatigue cracks in specimens of sheet alclad alloy D16AT and establishment of correlation relationship between duration of crack propagation and accumulated damage at the incubatory stage.

Specimens with side notch, linear sizes of which are shown at the fig. 2 have been tested.

Fatigue testing has been performed on a standard testing machine by axial tension with maximum cycle stress equal to 60.0; 70.0; 80.0 MPa with stress ratio $R = 0$.

Loading mode choice has been made taking ino account real conditions of aircraft structures loading.

During the testing following parameters were recorded: value of damage parameter at the stress concentrator and corresponding number of cycles at the incubatory stage, number of cycles to 1,0 mm long fatigue crack formation, crack length and corresponding number of cycles at the crack propagation stage; time of specimen failure.



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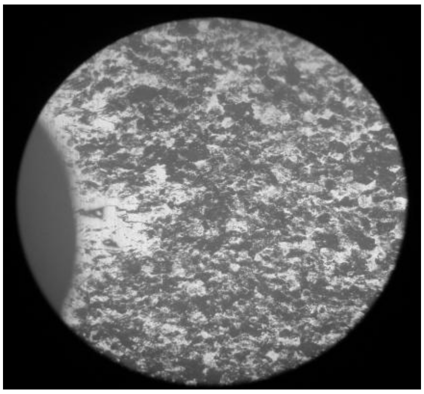

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Fig. 2. Fatigue testing specimen (*a*) and deformation relief at the stress concentrator (*b*)

The amount of performed tests allowed to obtain kinetic diagram of fatigue crack growth (Fig. 3), which leads to solution on the base of linear fracture mechanics.

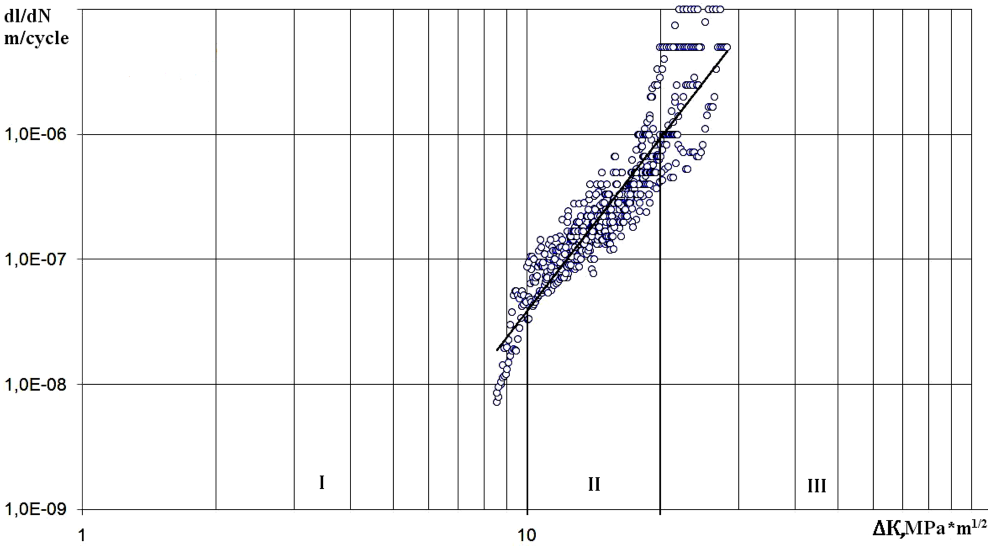

Fig. 3. Kinetic diagram of fatigue crack growth at specimens of sheet clad alloy *D16AT*, $R = 0$ (○ — experimental data, ▬ — experimental data approximation)

Initial data for construction of diagram of fatigue crack growth includes fatigue crack length *l* and corresponding number of loading cycles *n*, obtained from tests performed at maximum cycle stress $\sigma_{max} = 60{,}0 \cdot 70{,}0 \cdot 80{,}0$ MPa with stress ratio $R = 0$. Coefficients of Paris equation $C = 9 \cdot 10^{-15}$ and

q = 4,367 have been obtained by approximation of experimental data shown at the fig. 3.

Paris equation satisfactorily describes experimental data corresponding to double logarithmic scale of linear interval II of kinetic fatigue failure and does not correspond to the non-linear intervals (I and III). It is assumed that the crack is propagating through undamaged material which does not differ from its initial state.

Prediction of fatigue crack propagation process based on parameters of deformational relief at the stress concentrators

Earlier numerous researches have proved the possibility of number of cycles till crack initiation prediction based on the deformation relief parameters — its saturation and fractal dimensionality [2–4].

In the presented research monitoring of the damage parameter D at the stress concentrator during the incubatory stage of fatigue has been carried out. The limit value of the D parameter has been determined, i.e. the value which corresponds to complete saturation of relief and fatigue crack initiation. It has been assumed that after the crack initiation deformation relief density at the stress concentrator does not change, which has been proven experimentally. Value of the damage parameter D at the moment of crack initiation is referred to as critical damage parameter D_{crit}.

Critical damage parameter characterizes the material state at the crack initiation area, Regarding the fact that area of damage localization and deformation relief formation at the set loading parameters is equal to several millimeters, we can assume that there exists a close correlation relationship between the damage parameter D_{crit} and the crack propagation process characteristics.

At the fig. 4 as an example, dependence of propagation stage duration of the fatigue crack $N_{dur.}$, measured in thousands of cycles on the critical damage parameter D_{crit}, obtained by testing with maximum loading 70,0 MPa with asymmetry coefficient R = 0 is shown.

Given curve may be approximated by equation

$$N_{dur} = 4{,}9318 - 11{,}55\ \mathrm{Ln}\ (D_{crit}),$$

which makes it possible to predict the crack propagation stage duration with help of critical damage parameter D_{crit} at the stress concentrator.

Quality of the approximation is represented by the determination coefficient R^2 = 0,8139.

At the fig. 5 relationship between the rateed of crack propagation at its origination area, equal to 4,0 mm, and the critical damage parameter, which proves the existence of connection between local damage and crack propagation rate.

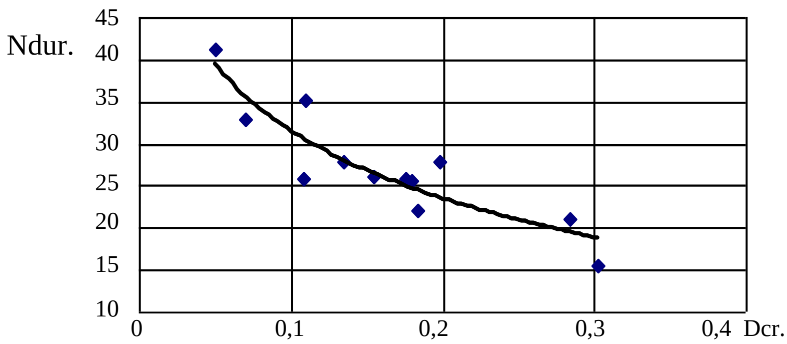

Fig. 4. Diagram of dependence of crack propagation stage duration on the critical damage parameter

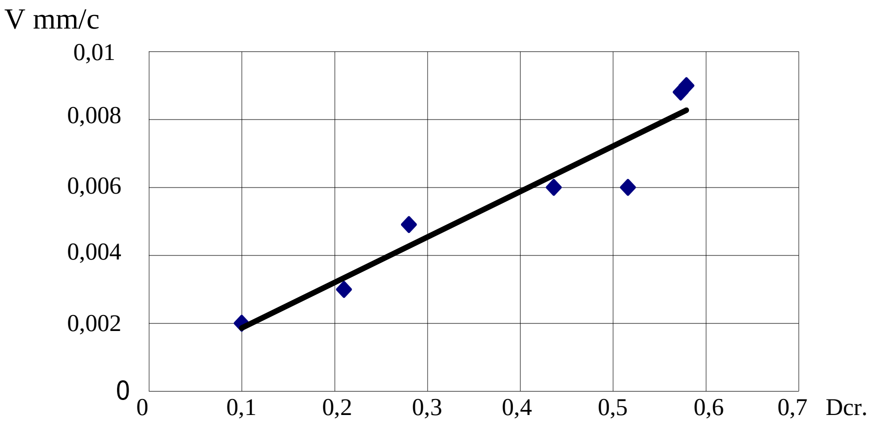

Fig. 5. Diagram of crack propagation speed dependence on the critical damage parameter

It's worth mentioning that influence of the deformation relief on the crack propagation rate persists after its propagation beyond the borders of the specified area, though closeness of the connection between the critical damage parameter and the growth rate decreases. Determination coefficients values R^2 for dependences of crack propagation rate on the critical damage parameter are shown in the table 1.

Table 1

Determination coefficients R^2 values for dependence of the crack propagation speed on the critical damage coefficient D_{crit}, for various crack lengths

Crack length, L, mm	0–4	4–8	8–12	12–16
Determination coefficient, R^2	0,915	0,8627	0,7339	0,5995

Results of crack propagation time prediction

Results of fatigue crack propagation time prediction for 12 specimens at the maximum loading of 70,0 MPa and the asymmetry coefficient R = 0 are given in the table 2.

Results of calculation performed by the two abovementioned approaches are represented by means of following notations:

$N_{dur.\ act}$ — actual duration of the crack propagation stage (10^3 cycles);

$N_{dur.\ Dcrit}$ — duration of the crack propagation stage determined by the critical damage parameter (10^3 cycles);

$N_{dur.fract.\ mech}$ — duration of the crack propagation stage determined by the fracture mechanics technique (10^3 cycles);

$N_{dur.\ act} - N_{dur.\ Dcrit}$ — crack propagation stage duration prediction error when determining with the help of critical damage parameter (10^3 cycles);

$N_{dur.\ act} - N_{dur.\ fract.mech}$ — crack propagation stage duration prediction error when determining with the help of fracture mechanics technique (10^3 cycles).

Durability estimation results have been obtained by the classic fracture mechanics approach from the expression. Results of fatigue crack propagation stage duration prediction based on the deformational relief at the stress concentrator saturation are given in the same table 2.

Table 2

Results of alloy D16AT specimens endurance prediction

Specimen	1	2	3	4	5	6	7	8	9	10	11	12
$N_{dur.\ act}$	41,2	22,1	25,7	25,8	25	25,8	24,6	15,6	21	35,2	28	33
$N_{dur.\ Dcrit}$	38,4	23,2	24,9	31,1	27,0	25,0	23,5	18,7	19,8	31,1	28,1	35,8
$N_{dur.fract.\ mec.}$	27,1	24,3	24,3	24,3	24,3	25,9	24,3	24,3	24,3	25,9	25,9	27,8
$N_{dur.\ act.} - N_{dur.\ Dcrit}$	2,8	–1,1	0,8	–5,3	–2	0,8	1,1	–3,1	1,2	4,1	–0,1	–2,8
$N_{dur.\ act} - N_{dur.\ fract.mech}$	14,1	–2,2	1,4	1,5	0,7	–0,1	0,3	–8,7	–3,3	9,3	2,1	5,2

As it is shown in the table above, absolute error of crack propagation stage duration prediction does not exceed $4{,}1\cdot10^3$ cycles, while the conventional approach only provides accuracy of $14{,}1\cdot10^3$ cycles.

Prediction of crack propagation in structure elements

Ability to predict duration of fatigue crack propagation stage based upon the deformation relief density at the stress concentrator has been proven by tests carried out on structure elements — specimens representing joint of fuselage skin with a stringer. Specimen diagram is shown on the fig. 6.

Tests have been carried out at the maximum cycle loading of 10,0 MPa and asymmetry coefficient R = 0.

At the diagram (Fig. 7) dependence of the crack propagation stage duration on the critical deformation relief near the riveted joint saturation is shown.

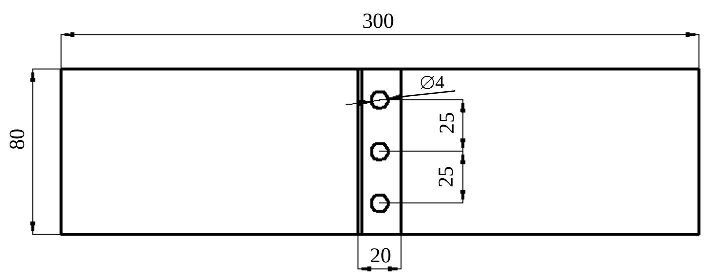

Fig. 6. Specimen representing riveted joint of fuselage skin with a stringer

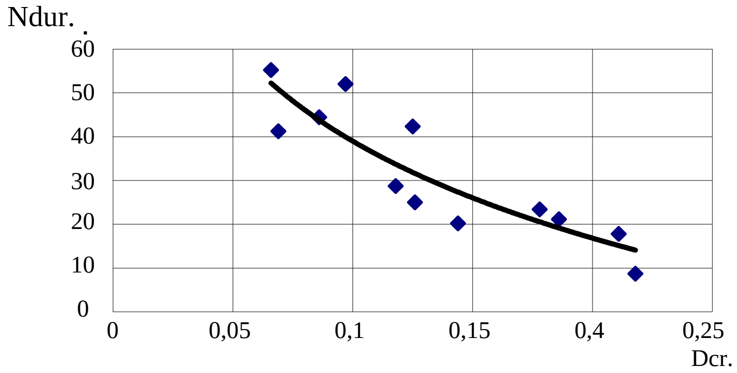

Fig. 7. Dependence of the crack propagation stage duration
on the critical deformation relief near the stress concentrator (riveted joint) saturation.

As well as at testing of specimens with side notch, the presented relation may be described by a logarithmic dependence.

Closeness of the relationship between the crack propagation stage duration and critical damage parameter *D* is characterized by a rather high determination coefficient $R^2 = 0{,}78$.

Conclusions

Assessment of sheet alclad aluminum alloys may be performed by the material damage parameters at the stress concentrator.

Method of alclad aluminum alloys durability prediction has been approved by cyclic loading of specimens simulating skin aircraft structures.

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