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DEFORMATION ROUGHNESS UNDER CYCLIC AND STATIC LOADS

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The experiments are aimed to develop a new non-destructive method for fatigue damage diagnostics. This method is based on monitoring deformation roughness which is formed on the surface of aluminum structural alloys. The evolution of this roughness near the stress concentrator has been monitored at various stages of fatigue life under the stress level close to the operational stress level on the fuselage skin of modern aircraft. The deformation relief under static loads is represented as well.

Introduction

Metal fatigue is one of the main causes of the aircraft crashes, leading to considerable human victims and financial expenses.

The current generation of civil transport aircraft were designed for at least 20 to 25 years and up to 80 000 flights. These design service goals are exceeded by many operators of jets and turboprops.

Future aircraft types are designed for the same goals, but structure with higher fatigue life and higher damage tolerance capability are required to minimize the maintenance costs and to comply with the requirements of the operator and the enhanced airworthiness regulations. Taking into consideration the importance of the problem, a set of International Civil Aviation Organization documents, as well as European Joint Aviation Regulations, US Federal Aviation Regulation, Airworthiness Regulations of Russia and Ukraine consider the aircraft fatigue analysis as a mandatory procedure for providing aircraft reliability and service life. For example, according to the “FAR-25, Sec. 25.571 – Damage – tolerance and fatigue evaluation of structure”, evaluation of the strength, detail design, and fabrication must show that catastrophic failure due to fatigue, corrosion, manufacturing defects, or accidental damage, will be avoided throughout the operational life of the airplane. This evaluation must be conducted for each part of the structure that could contribute to a catastrophic failure (such as wing, empennage, control surfaces and their systems, the fuselage, engine mounting, landing gear, and their related primary attachments).

Fatigue analysis includes a set of theoretical and experimental procedures, but taking into account the complicated character of aircraft loads in operation and the stochastic nature of metal fatigue, one may assume that only reliable adequate instrumental diagnostic of actual accumulated fatigue damage can prevent unexpected failure of structures.

A set of diagnostic methods are based on using specimen-witness, which are mounted on the surface of the object to be inspected. Devices are usually called fatigue sensors or indicators of the fatigue damage.

The description of the most effective device is given in [1; 2]. These indicators subjected to the operating spectrum of cyclic loads, change their state or even may be destroyed. That indicates the degree of damage accumulation in the investigated structural element.

One of the most stressed parts of the aircraft structure is skin [3]. For the skin of civil aircraft, aluminum alloys D-16 and V-95 are widely used in Ukraine and Russia, which are almost analogous to 2024T3 and 7075T6, according to AISI-SAE designation. The main alloying elements of D-16 and 2024T3 are copper and magnesium, while V-95 and 7075T6 contain about 5% of zinc.

In order to reduce the possible corrosion problems, some sheets of mentioned alloys are often covered with a layer of pure aluminum (for D-16 and 2024 T3) or with a layer of Al with 1,0% of Zn (for V-95 and 7075 T6).

The thickness of clad layer is in the range from 4 to 7% of the total sheet thickness.

It’s well known that surface state plays a specific role in the fatigue life of materials. Damage evolution in cyclic straining starts predominantly on the surface of the materials and is represented by the formation of the surface relief. Nucleation of fatigue cracks occurs at various surface irregularities (surface notches) that act as stress concentrators.

The cyclic loading under certain conditions leads to strain localization zones of highly deformable material layers called persistent slip bands (PSBs). These PSBs have been connected with the evolution of a characteristic dislocation substructure and the formation of extrusion/intrusion slip markings on the specimen surface.

Aluminium and some of its alloys, which may be used for cladding, are considered so called PSBs type materials [2], because when they are subjected to cyclic loading, PSBs appear and develop on their surfaces.

The general scheme of the PSB formation [4] is shown in fig. 1.

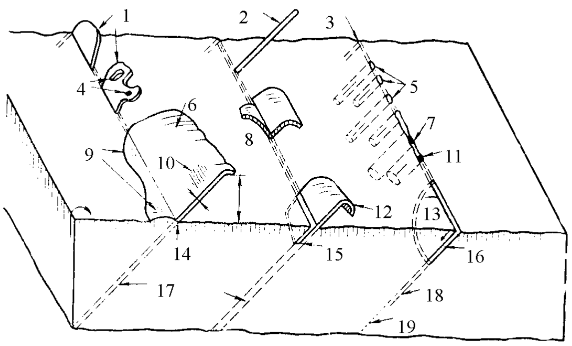

Fig. 1. Persistent slip band (PSB) formation in plastic metals:
1, 2, 4, 8, 12, 14, 15 – extrusions; *3* – tracks of coarse slip; *5* – pores of different depths in PSB; *6* – slip lines on extrusions; *7* – coalescence of some pores; *9* – surface relief near extrusion; *10* – microbands; *11* – microbands; *13* – crack growth direction; *16* – intrusions; *17, 18* – PSB; *19* – dislocations

It may be assumed that the above mentioned property can be used for indication of the accumulated deformation damage.
Thus, the information about the accumulated fatigue damage and residual life may be obtained by analysis of the surface state in critical points of structures, which are made of clad sheets of aluminum alloys, such as aircraft fuselage skin. A fragment of the investigation results based on this principle are represented below.

Experimental procedure

Metallographic investigation of the chosen metals was performed using the recommendation [5].
Grain size measurement has been conducted directly with microscopic investigation (table).
Flat specimens with a hole in the center (fig. 2), in order to induce fracture localization were used in fatigue test procedure.

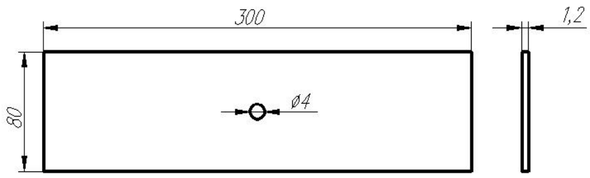

Fig. 2. Specimen for fatigue test

Such stress concentrator indicates the point for checking as well. The thickness of the specimen is 1,5 mm and the diameter of the hole is 4 mm.
These dimensions were chosen because the 1,5 mm sheets of thickness are used in many cases for aircraft skin production, where as the 4 mm hole imitates a constructive hole for rivets. Riveted aluminum structures are found to varying degrees on virtually all aircraft. In aircraft structures rivets are used to joint sheets of the skin, or mount 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.
The cyclic deformation test has been carried out with a hydraulic pulsating machine MUP-20. Tests have been performed under load control, at frequency of 11 Hz and load ratio ($R = \sigma_{min}/\sigma_{max}$) of $R = 0$. The shape of loading cycle is sinusoidal.
All damage parameter measurements have been performed near the stress concentrator, where stress level is maximum.
Deformation relief under static loads has been also observed on the surface of the alloy D-16 specimens clad by aluminium. Specimens have been used, manufactured in accordance to standard (fig. 3).

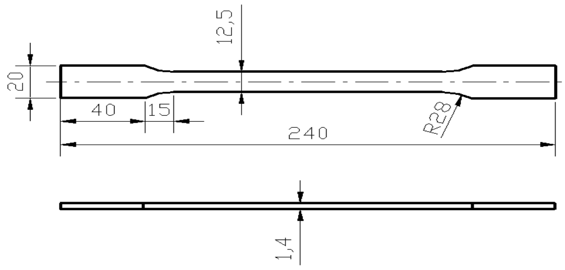

Fig. 3. Specimen for static loads

The test has been performed by test machine for static loads FP-10. The rate of deformation was 2 mm per minute. Special equipment was designed for deformation roughness monitoring. The main objective was to use standardized systems, which are in mass production, having stable characteristics and relatively low cost. The present investigation of deformation roughness and the quantitative estimation of the accumulated fatigue damage have been conducted with the system consisting of metallographic light microscope with enlargement about X400, digital camera with the number of pixels 1600× 1200 and portable PC.

Grain sizes of investigated alloys

Alloy designation	D-16	2024T3	7075T6
Average grain diameter in the rolling direction, μm	41,8	83,3	42,7
Average grain diameter perpendicular to rolling direction, μm	39,0	66,7	41,8
Average grain area, μ^2	$1{,}6\cdot10^3$	$5{,}6\cdot10^3$	$1{,}8\cdot10^3$

The three-dimensional character of observed roughness pattern and its correspondence to the known scheme of intrusions and extrusions formation [5] have been confirmed by means of Scanning Electron Microscopy (SEM) investigation with the help of a Zeiss DSM950 microscope.

Experimental results

Previous researches on aluminum single crystals under fatigue [1; 2] conducted at the National Aviation University and the published results of other authors [6; 7], showed a close correlation connection of the accumulated fatigue damage with the density of PSBs. The dependence of fractal dimension of the surface pattern on accumulated damage has been proved as well [1]. These results are the background for the proposed method. So, it was proposed to use the same approach for analysis of surface state of poly crystal structural materials [8].

The images of cyclically loaded specimen surfaces have been processed by special software. The developed program saves the surface images in BMP format and gives the possibility to determine the damage parameter "D" quantitatively. Such parameter is equal to the area of specimen surface with deformation tracks (PSBs) divided by total considered surface.

The researches have been carried out in the wide range of stress conditions. A set of experimental curves that express the dependence of accumulated damage parameter on the number of cycles have been obtained.

All curves as well as presented below have been obtained by the approximation with exponential function. As example, the result of fatigue test of D-16 specimen and damage monitoring under the maximum stress 81,7 MPa are presented. It expresses the relationship of damage parameter "D" and current number of cycles N_C (fig. 4).

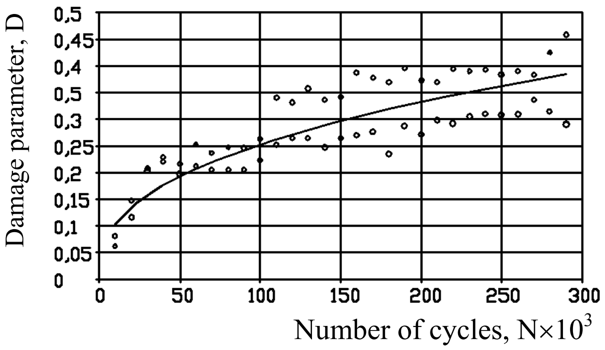

Fig. 4. The dependence of damage parameter "D" on the number of load cycles

Results presented have been approximated by the function $y = 0{,}0027\, x^{0{,}394}$ with correlation coefficient R^2=0,7865.

The test finished after the nucleation of fatigue crack of 1,0 mm length, so a crack length of 1,0 mm has been adopted as the critical state condition.

As it is seen from the graph, the minimum scatter is on the initial stage of the fatigue process, whereas the final stage of the damage accumulation process has maximum level of scatter.

The more complex situation for fatigue failure prediction is in the random action of loads. The further research plan intends to carry out testing under a wide range of loads operation regimes. Both regular and program loads regimes will be materialized in order to simulate service conditions.

Indication of strain level under static loads is interested for some practical task, therefore some observation of surface state under static deformation have been conducted as well.

A set of specimens of aluminium alloy D-16 have been tested under maximum relative strain 0,66; 0,83; 0,85; 1,12; 1,19; 2,15; 2,32; 5,22; 12,15 percents accordingly.

Formation and evolution of the deformation relief were observed, but in contrast to fatigue regimes surface pattern have been observed only under the relative strain 2% and more.

So, in the case of static loads deformation relief can indicate only considerably close to ultimate strain and loads.

As 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 means of generalized load researches for the particular airplane type, in case of insufficient data - with the help of supposed use of aircraft.

2. Structure portions to be investigated are determined. The location of a possible damage can be determined by analysis or on the basis of endurance tests for the whole structure or its separate elements. If the estimation is performed by analysis, the following parameters are taken into account:

– strain measurement data for determination of places of high stresses concentration and magnitude of the concentration;

– places where residual deformations are arisen during previous tests;

– places of possible fatigue damages defined by fatigue analysis; d) structure places which according to operation experience of similar structural elements are susceptible to fatigue.

3. Laboratory fatigue tests of structure elements (specimens) are carried out to create data bank about evolution of an element surface state. 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 under different load levels, different sequences of load application, etc. The test program is scheduled taking into account operating range of loads. For each state the factor of service life is calculated as a relation 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 state evaluation of an inspected part of structure is conducted by estimation of damage parameters and comparison with those laboratory testes specimen, having the same value of damage parameter and estimated life (the factor of service life exhausting). Our researches have shown, that one of the appropriate damage parameter might be relative area of surface with deformation traces.

Conclusion

Accumulated fatigue damage of alclad aluminium alloy D-16 of Ukrainian manufacturing as well as 2024T3 and 7075T6 alloys of western industry may be performed by the analysis of surface pattern, created by the cyclic loads.

As the deformation relief on the surface of cladding layer may be observed at very first cycles of loads, the visual diagnostic of initial stages of fatigue damage is possible.

The area of the surface with slip lines corresponds with the level of accumulated damage.

The new approach may be used for indication of more dangerous points of aircraft structures, for prediction of fatigue crack under the full scale test of aircraft structures as well as for residual service life estimation.

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Деформаційний рельєф при циклічному і статичному навантаженні

Наведено результати експериментів, які спрямовані на створення нового інструментального методу діагностики втомного пошкодження, який базується на моніторингу деформаційного рельєфу, що формується на поверхні алюмінієвих конструкційних сплавів. Розглянуто еволюцію рельєфу поблизу концентратора напружень на різних стадіях втомного пошкодження при циклічних напруженнях, близьких до тих, що діють в обшивці фюзеляжу сучасних літаків, та деформація рельєфу при статичному навантаженні.

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Деформационный рельеф при циклическом и статическом нагружении

Приведены результаты экспериментов, направленных на создание нового инструментального метода диагностики усталостного повреждения, базирующегося на мониторинге деформационного рельефа, формирующегося на поверхности алюминиевых конструкционных сплавов. Рассмотрена эволюция рельефа вблизи концентратора напряжений на различных стадиях усталостного повреждения при циклических напряжениях, близких к действующим в обшивке фюзеляжа современных самолетов, и деформация рельефа при статическом нагружении.