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SKIN SURFACE EXTRUSION/INTRUSION STRUCTURE AS AN INDICATOR OF AGING AIRCRAFT FATIGUE

A new method for fatigue damage detection is proposed. The new method extends earlier proposed and verified approach for fatigue damage assessment based on the quantitative analysis of surface deformation relief on aluminium and some of its alloys. It will be shown that the fundamental property of hidden persistent slip bands to be revealed after secondary cyclical loading can be used for the fatigue analysis of aging aircraft.

Key words: *aging aircraft, aircraft fatigue, extrusion/intrusion, persistent slip bands, fatigue assessment*

Introduction

The required aircraft service life is defined at the conceptual design stage, but different operational conditions of individual planes cause the dispersions of actual exhaustion of the components bearing capacity.

Apparently, the necessity of structural health monitoring exists for the individual machines. Metal fatigue is a crucial process for aircraft bearing components and, therefore, it requires monitoring to predict or prevent fracture.

There have been several attempts to create fatigue damage monitoring systems and sensors. Several sensors/indicators, as well as methods for direct fatigue monitoring, have been developed at the National Aviation University (Kyiv, Ukraine) [1-6].

Fatigue monitoring methods developed at the National Aviation University are based on the phenomena of deformation relief formation on the metal surface. Deformation relief consists of extrusions, intrusions and persistent slip bands (PSBs) formed under the action of repeated loads.

Two methods based on the same principle include: a) application of fatigue sensors/indicators; and b) direct optical monitoring of surface pattern.

Effectiveness of these methods was proved by numerous experiments in the lab, but their practical application has some limitations.

The procedure of the fatigue assessment begins with the installation of a sensors (first method), or by polishing the inspected surface spot and an optical diagnostic (second method). The obtained data refer only to the period from the start of monitoring and don't indicate total accumulated fatigue damage.

At the same time there is strong necessity to assess the technical state of airplanes being operated for a long time without previously conducted fatigue monitoring.

In the research paper the possibility to check accumulated fatigue damage for structures initially being operated without fatigue monitoring is considered. For this purpose, the original method for persistent slip bands detection has been proposed. The method can be used for materials with cladding layer of aluminum.

Cladding layer and its effects on fatigue

For the tests directed on the new method being developed the aluminium alloy D16AT has been selected. Investigated alloy D16AT, as well as its closest analogous 2024T3, refers to so called alclad materials which are corrosion-resistant aluminium sheets alloy. The sheets are formed from aluminum foil metallurgically bonded to high-strength aluminium alloy core material.

Despite the positive effect against corrosion, there are some aspects of the alclad alloys application that require fatigue analysis.

The usual assumption for clad duralumin is that the lifetime of such materials is lower, i.e. the Wohler's curve should lie below the curve valid for non-clad duralumin [7-9]. The effects of cladding and anodizing on flight simulation (gust spectrum) fatigue was proved for notched specimens and riveted lap joints of 2024-T3 and 7475-T761 aluminium alloy sheets, specimens of LC9 cs alloy.

In the LC9cs alloy, cracks initiated in the cladding layer and grew as corner cracks into the core material [9]. To account for this growth, the stress intensity factor solution for corner cracks was modified to approximate model cracks in a multiple-layer medium. The yield stress of the cladding was estimated to be about 50 MPa. In the investigated specimens, the cladding layer always yielded and developed multiple cracks from slip-band formation along the edges of the notch.

In the research carried out at the National Aviation University it was also proved that the normal cladding layer has a deleterious effect on the fatigue resistance and the effectiveness of the protection of aluminium alloys from corrosion, though there is a slight rise in their corrosion-fatigue strength. The fatigue life and the corrosion-fatigue life of sheet materials of the aluminium alloys D16AT and V95 depend on the thickness of the cladding layer. [10].

Thus, being a weak member of the two layers composition of the alclad alloys, the state of cladding layer reflects the damage process in advance to the damage of core material.

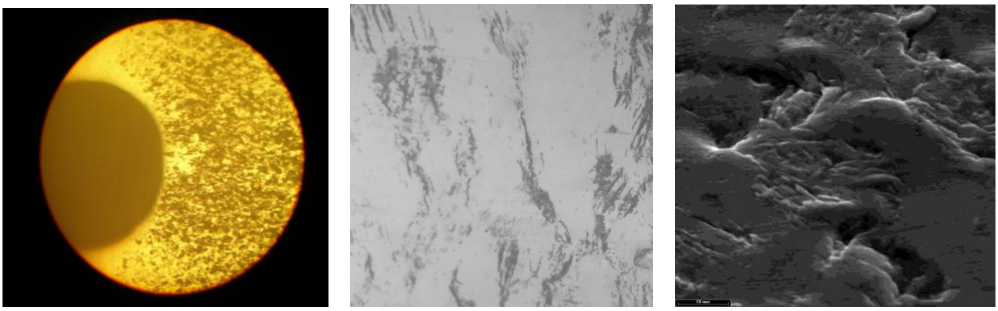
Nature of surface deformation relief

Aluminium and some its alloys refer to the materials which react on mechanical loading by formation of Persistent Slip Bands (PSBs). As it was shown by many researchers, beginning from tests conducted by Forsyth in 1953 [11], fatigue cracks initiate from the areas where PSBs emerge on the surface. Thus, PSBs reveal critical sites of the components. Together with extrusions, intrusions, some features of grain rotation, PSBs form the surface pattern called by many authors as "deformation relief".

It was shown that in a Al-Cu alloy thin ribbon of the metal with thickness of 0,1 μm and 10 μm length extruded at the specimen surface from persistent slip bands. A quantitative measurement of the height of slip steps formed during the fatigue of Cu single crystals has been conducted by authors of papers [12]. Using the interferometric measurement, they showed that surface slip steps form in proportion to the applied plastic strain.

Extrusions rise above and intrusions fall below the surface of metal due to the movement of dislocations along the slip planes. The dimensions of extrusions and intrusions depend on the material and stress-strain state.

Surface deformation relief images observed on alclad D16AT with light and scan microscopes are shown on figure 1.



a) b) c)

Figure 1: The surface deformation relief images observed on D16AT under fatigue with: light microscopy, 24^{x}; b - light microscopy, 300^{x}; c – scan microscopy, 1620^{x}.

Evolution of deformation relief under fatigue

The relationship between the accumulated fatigue damage and the intensity (saturation) of deformation relief was established both for the single crystals and for the polycrystalline metals.

The concept of single crystals fatigue indicators was discussed in work [1]. The 20-mm long fatigue indicator was made of single-crystal aluminium foil (99.99% wt Al). The indicator was stuck on a flat specimen 1.2 mm thick. The maximum applied stress in two fatigue tests were 140 and 180 MPa. The frequency of loading was 9.8 cycles/s. The indicator surface was periodically inspected by means of a microscope with a 200^{x} enlargement. The strong relationship between slip lines density and number of cycles has been established.

The single crystal fatigue sensor was proved to be an effective tool for fatigue monitoring, but the practical application has a restricted area due to the limitation of adhesive-bonded sensor-to-specimen joint. This problem is avoided by application of the direct optical inspection of some materials referring to so called persistent slip band metals, i.e. materials where persistent slip bands and other features of deformation relief are seen on the surface after fatigue loading.

Deformation relief has been observed on the surface of cladding layer of the alloys D16AT, B95, 2024T3, 7075T6 subjected to the cyclic loading [2-6]. Specimens for testing were made of thin sheets used for aircraft skin manufacturing. Tests were carried out under a wide range of axial, bending and combined loads of bending and twist. As a result of polycrystalline specimens tests, the methods for the direct fatigue monitoring and fatigue indicator of new generation were introduced [2-6].

Among the numerous quantitative parameters of deformation relief the most adequate and promising are: a) relief saturation, expressed as parameter D, and b) fractal dimension $D_{p/s}$ calculated on the base of the relief clusters perimeter to area ratio [4]. For the calculation of both parameters the two-dimensional digital images are used. For the optical inspection the small 1.0 mm spot on the surface is prepared by the mechanical polishing with diamond pastes.

The damage parameter D calculated as a ratio of the surface area with slip bands, intrusions, extrusions to the total local area is controlled by the light microscope. As an example, the result of fatigue test of D16AT specimens and damage monitoring under axial tension with the maximum stresses 76,9 MPa; 81,7 MPa; 96,2 MPa; 105,8 MPa; 115,4 MPa; 129,8 MPa, 134,6 MPa and stress ratio R=0 and frequency 11 Hz are presented. It expresses the relationship between the damage parameter D and current number of cycles N_i (figure 2).

The tests were stopped after the nucleation of 1.0 mm fatigue crack as it has been considered as the critical state condition.

One of the current researches proves the possibility to use deformation relief when the inspected component works under the multi-axial loading [5,6]. The proposed concept of equivalent relief for multi-axial fatigue extends the area of deformation relief criteria application for fatigue damage assessment.

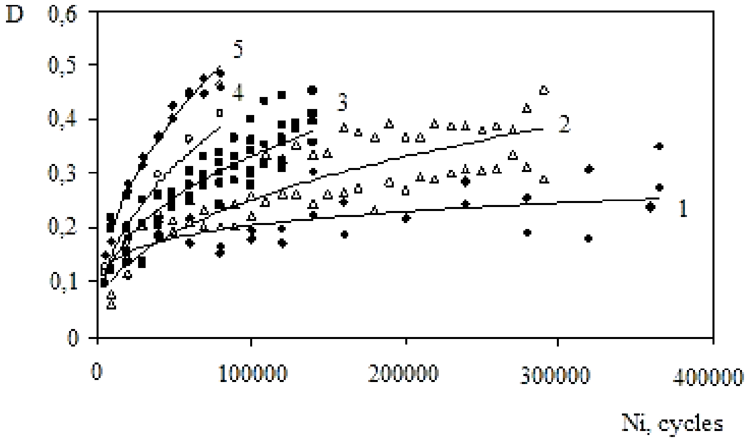


Figure 2: The evolution of damage parameter *D* on the surface of alclad aluminium alloy D16AT under cyclic loading: 1- σ_{max}=76,9 MPa; 2 - σ_{max}=81,7 MPa; 3 - σ_{max}=96,2 MPa; 4 - σ_{max}=115,4 MPa; 5 - σ_{max}=134,6 MPa. Stress ratio R=0, frequency 11Hz.

The drawback of the methods mentioned above is that the revealed damage reflects only the period of monitoring. The enhanced method discussed in this paper allows assessment of the total fatigue damage by the surface inspection at any moment of aircraft operation and even at the close to retirement aircraft age (aging aircraft).

Aging aircraft

The age of an aircraft is expressed by three parameters, namely the chronological age (in years), the number of flights, and the number of flight hours.

The average retirement age for all commercial jet aircrafts remains slightly less than 26 years [13]. The narrow body fleet average age is around a year more and the wide body average is a year less.

Over 2,000 passenger aircrafts are currently inactive being in storage, with an average age of 21 years. Over 60% of these (and almost 80% of those over 15 years old) will not return to commercial service.

Apparently, the demand on aircraft to be returned to commercial service varies from country to country and but is more true for poorer countries whereas the presented data reveals the opportunities for the active fleet to be recovered.

“Persistency” of slip bands as a phenomenon for assessment accumulated damage at the latest stages of metal fatigue

As it is known from the early works on PSBs nature, once formed, PSBs arise again after polishing and the following repeated loading. This fundamental property of the PSBs is considered here as a way to assess accumulated fatigue damage of aircraft even when the inspection is conducted for aging planes. As the monitoring from very beginning of operation is impossible for such structure the task of fatigue assessment seems to be too complex.

Nevertheless, the possibilities to reveal accumulated damage by the detection of hidden slip process exist.

The flat specimens of alclad D16AT alloy were investigated in the fatigue test procedure. The hole in the center of specimen indicates the stress concentrator and the points for surface investigation. The specimen is 1,5 mm thick, the diameter of the hole is 4 mm. Maximum stress of the cycle is σ_{max}=115,4 MPa and stress ratio is R=0.

After the surface polishing the cyclic loading was carried out and deformation relief was monitored (curve A-B, figure 3). Then, second polishing was carried out to remove appeared surface PSBs pattern. Specimen was loaded again with smaller number of cycles under the same stress level (curve C-D, figure 3). Surface relief of larger intensity with the same principle features has been revealed after the secondary loading. Thus, the secondary deformation pattern reflects accumulated damage on the stage “from zero” to the first fatigue inspection and from the first inspection to current check.

For quantitative assessment of the accumulated fatigue damage, the damage parameter *D* should be calculated with the software according to the procedure used earlier [2-6]. The intensity of the surface relief grows according to the logarithmic law.

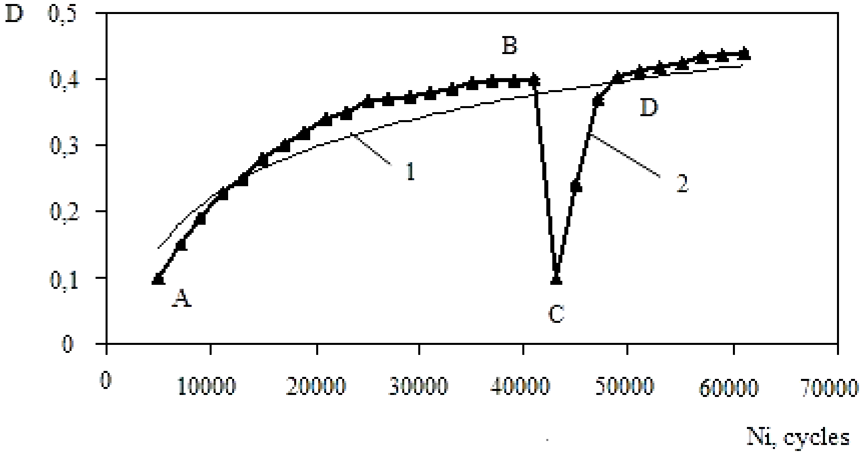


Figure 3: Fatigue damage evolution: 1- proved character of deformation relief saturation and corresponded damage growth; 2 - result of monitoring with primary and secondary polishing.

On this basis the following procedure for the inspection of the structures with certain accumulated damage can be proposed:

a) It is presumed that the damage grows from the “zero” state to the “first check” state accordantly to the beforehand revealed character. The deformation relief on the surface of structural components is hidden because the surface is not prepared by polishing;

b) After the certain operational time the critical area of component gets polished;

c) After the polishing the airplane operation continues and deformation relief monitoring starts as well;

d) After the minimized number of operational cycles, the optical analysis is carried out with assessment of the damage accumulated at the initial stage (before polishing) and after polishing.

For the further development of the method the following objectives must be experimentally solved: a) the depth of polishing must be established; b) the minimum number of cycles for the persistent slip bands recover must be found.

Assessment of the polishing depth

The assessment of the accumulated fatigue requires special preparation (polishing) of specimen's surface. This procedure is carried out twice in the laboratory tests aimed on the method's details development. First, polishing is conducted before monitoring starts and second polishing at the "check point".

At the same time, it should be mentioned that the practical application of the method presumes the polishing only once while inspecting.

The assessment of the polishing depth is based on the results of the analysis of extrusion/intrusion geometry made with scan microscope and interference noncontact profilometer.

For example, for the specimens of aluminium alloy D16AT with cladding by pure aluminum loaded under the maximum level of stress 120 MPa and stress ratio R=0 with frequency of loading 11Hz, the height of extrusions as well as the depth of intrusions were close to 1.0 µm. These are extrusions/intrusions parameters nearby stress concentrator. At the same time at the distance 1.25 мм from stress concentrator the height of extrusions was 0,6 µm, and the depth of intrusions – 0.4 µm.

Taking into account the results of tests the depth of removed metal was accepted equal to 1.5 µm. This technique should be applied for the laboratory tests at the "check point".

The number of cycles to make persistent slip bands revealed

The number of cycles which allows detection of the hidden PSBs remains to be the most complex question of the discussed method. It depends on many factors as follow: a) the maximum stresses; b) parameters of cycles; c) fatigue damage accumulated before check point inspection; d) depth of primary and secondary polishing, etc.

For current tests the first signs of revealed deformation pattern were observed after 5000 cycles of renewed loading. In service practice the loading to reveal surface pattern is carried out after the polishing by operational loads with number of cycles (flights) determined beforehand by the special research.

Conclusions

The developed earlier methods for fatigue damage assessment based on the quantitative analysis of surface deformation relief of new structures can be extended to the method for aging aircraft fatigue analysis.

To provide the fatigue monitoring after partly exhausting service life, the fundamental feature of persistent slip bands to recover under the continuation of loading is proposed to be use.

The proposed method is now under development. The considerations presented in the paper and preliminary experimental results would suggest the cycle of research be continued.

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ЕКСТРУЗІЙНО-ІНТРУЗІЙНА СТРУКТУРА ПОВЕРХНІ ОБШИВКИ ЛІТАКА ЯК ПОКАЗНИК ВТОМНОГО ПОШКОДЖЕННЯ СТАРІЮЧИХ ЛІТАКІВ

В статті розглядається новий підхід до визначення накопиченого втомного пошкодження конструкцій літаків, які мають значний наліт і потребують оцінки фактичного залишкового ресурсу.

В якості показника накопиченого втомного пошкодження розглядається насиченість деформаційного рельєфу поверхні обшивки літака, виготовленої з плакованих алюмінієвих сплавів.

Деформаційний рельєф є сукупністю екструзій, інтрузій та стійких смуг ковзання, які формуються і розвиваються в процесі циклічного навантажування. Можливість кількісної оцінки деформаційного рельєфу доведена в попередніх роботах авторів.

Проблемним моментом раніше запропонованого методу була необхідність моніторингу стану поверхні від самого початку експлуатації літака, тому що деформаційний рельєф виявлявся тільки на попередньо підготовлених поліруванням ділянках поверхні і відображав пошкодження, накопичене за період моніторингу. Це обмежувало можливості оцінки стану елементів конструкції старіючого парку літаків.

В основі нового методу лежить фундаментальна властивість смуг ковзання – їх стійкість, тобто здібність повторно виходити на поверхню після полірування поверхні і циклічного навантажування.

Актуальність методу підтверджена результатами статистичного дослідження, яке показало, що в теперішній час в світі не використовується більше 2000 літаків старіючого парку літаків.

Враховуючі велику кількість літаків, експлуатація яких припинена в зв’язку з невизначеністю фактичного залишкового ресурсу, новий метод має значне практичне значення.

В статті наведено дані про природу деформаційного рельєфу поверхні, показано, що екструзії, інтрузії та смуги ковзання можна спостерігати на поверхні плакованих конструкційних алюмінієвих сплавів засобами оптичної мікроскопії, наведено дані про еволюцію насиченості деформаційного рельєфу поверхні.

Представлено результати оригінальних експериментів, які вказують на можливість виявлення стійких смуг ковзання на обшивці літаків зі значним напрацюванням і кількісної оцінки накопиченого втомного пошкодження.

Ключові слова: старіння літака, авіаційна втома, екструзія, інтрузія, стійкі смуги ковзання, оцінка втомного пошкодження.

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