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Extrusion/intrusion structures as quantitative indicators of accumulated fatigue damage

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ABSTRACT

Two approaches to aircraft fatigue monitoring by the computer-aided analysis of surface structures are described: (a) application of fatigue indicators attached to the aircraft unit; (b) the direct observation of the alclad aluminium alloys surface. The evolution of aluminium surface state has been monitored at various fatigue loading regimes. Some parameters have been used for the quantitative analysis of surface structures: (a) density of slip lines for single-crystals; (b) intensity and fractal dimensions of the deformation relief for polycrystalline aluminium. The possibility of a fatigue process prediction both at crack initiation stage and fatigue crack propagation stage is shown.

1. Introduction

Due to the development of analytical and tools methods of fatigue damage accumulation monitoring the failure rate in aircraft structures caused by metal fatigue has decreased last years. Nevertheless, metal fatigue is still one of the main reasons of unforeseen crashes. Taking into consideration the importance of the problem, a set of International Civil Aviation Organization (ICAO) documents, as well as European Joint Aviation Regulations (JAR), US Federal Aviation Regulation (FAR), and Airworthiness Regulations of Russia and Ukraine consider the aircraft fatigue analysis as a mandatory procedure for providing aircraft reliability and service life.

Components that fail by fatigue usually undergo three separate stages of damage: (a) fatigue initiation; (b) propagation of the fatigue crack; (c) final sudden failure.

It is obvious that the quicker you reveal the initial stage of fatigue the less probability of disastrous failure is.

Fatigue analysis includes a set of theoretical and experimental procedures, but taking into account the complicated character of aircraft loading during operation 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.

There are two approaches to instrumental estimation of accumulated fatigue damage: (a) application of fatigue indicators (sensors, specimen-witnesses); (b) direct material state diagnostic.

A set of diagnostic methods use fatigue indicators, mounted on the surface of the object to be inspected. The indicators subjected to the spectrum of operating cyclic loads, change their state or may be even destroyed and in such a way indicate the degree of damage in the tested structural element.

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

Our investigations show that quantitative estimation of fatigue damage accumulation may effectively be conducted by computer-aided optical analysis of the surface state of the metal foil indicators, attached to the investigated units or by direct observation of the aircraft skin surface state if the skin is made of alclad alloys.

2. Single-crystal fatigue indicators

The single-crystal fatigue damage indicator was created at the National Aviation University [1]. The quantitative parameter of the accumulated fatigue damage in this concept is the density of the slip lines on the single-crystal surface.

At the first stage of the researches the single-crystal indicator attached to the specimen was loaded by regular regime.

The persistent slip band appeared on the single-crystal surface after several thousand of cycles.

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The density of slip lines calculation was performed with light microscope with magnification 400×.

The tests conducted have shown the close liner relationship between the density of slip lines and the number of cycles.

At the following stage of research programme we tried to investigate diagnostic opportunities in the more complex programme regime.

The cyclic loading was performed at two stages with transition from the lower level of loads (maximum stress of cycle equals 140 MPa) to the higher (maximum stress of cycle equals 180 MPa). After fatigue loading the single overload was applied. The magnitude of the stress under the static overload was 400 MPa.

The slip lines formed under cyclic loading were located at the angle of 82° to the axis of loading. The angle of the slip lines inclination after static loading was 57°. This distinguishes them from the bands of fatigue nature.

Thus, the possibility to monitor damage caused by complex fatigue loading with the static overloads, was demonstrated (Fig. 1). In Fig. 1 k is the density of slip lines (number of lines per unit of length), N – the number of cycles.

3. Computer-aided optical analysis of intrusion/extrusion structure of alclad aluminium alloys

For a skin of civil aircraft, aluminium alloys D16AT and V95 are widely used in Ukraine and Russia, which are almost analogous to 2024T3 and 7075T6, according to AISI-SAE designation. The main alloying components of D16AT and 2024T3 are copper and magnesium, while V95 and 7075T6 contain about 5% of zinc. In order to reduce the possible corrosion process, some sheets of mentioned alloys are often covered with a layer of pure aluminium (for D16AT and 2024T3) or with a layer of Al with 1.0% of Zn (for V95 and 7075T6). The thickness of clad layer is ranging from 4 to 7% of the total sheet thickness.

For polycrystalline metals as well as for single-crystals, the cyclic loading under certain conditions leads to strain localization zones called persistent slip bands. These PSB's are connected with the evolution of a dislocation substructure and the formation of extrusion/intrusion slip markings on the specimen surface. In Fig. 2 the scheme of the extrusions, intrusions and slip bands formation is presented.

Aluminium and some of its alloys, which may be used for cladding, are considered to be so called persistent slip bands (PSBs) type materials, because when they are subjected to cyclic loading, PSBs appear and develop on their surfaces [3].

Relief intensity depends on the stress level, distribution of the stress near the stress concentrator and the number of cycles.

Flat specimens with a hole in the centre, in order to induce fracture localization were used in a presented fatigue test procedure.

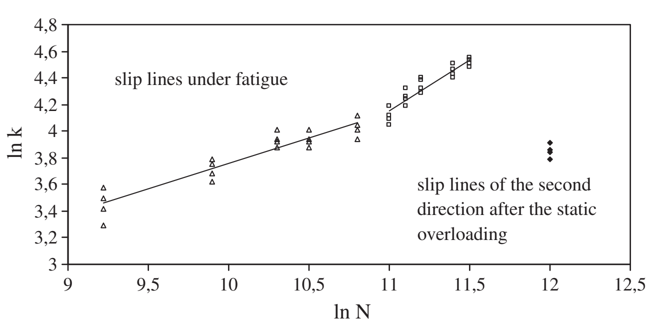

Fig. 1. Relationship between the slip lines density (k) and the number of cycles, N.

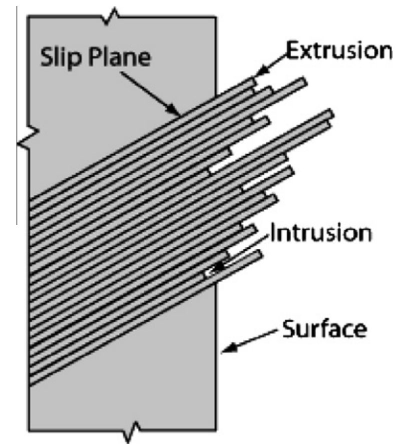

Fig. 2. The scheme of the extrusions, intrusions and slip bands formation [2].

Such stress concentrator indicates the point for optical investigation as well. The thickness of the specimen is 1.5 mm and the diameter of the hole is 4.0 mm. These dimensions were chosen because sheets of 1.5 mm thickness are used in many cases for aircraft skin production, where as 4 mm hole imitates a constructive hole for rivets. In aircraft structures rivets are used to joint sheets of the skin or mount the 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.

Tests have been performed under wide spectrum of loads at frequency of 11 Hz and load ratio $R = 0$.

The procedure of accumulated fatigue damage estimation used in the research includes the analysis of digital images of the deformation relief investigated by the light microscope.

Correspondence of the studied structures to the well-known scheme of the extrusion and intrusion formation [3] was proved by the scan microscope investigation.

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 Fig. 3.

The dislocation structure of deformation relief was investigated as well. It was revealed that several kinds of dislocation substructures co-exist inside the surface relief: extended dislocation substructure (Fig. 4a), chaotic dislocation in the grain (Fig. 4b), chaotic dislocations inside the strip-like dislocation (Fig. 4c), subgrain with inner block substructure (Fig. 4d), honeycomb structure (Fig. 4e).

The images of cyclically loaded specimen surfaces have been processed by special software. The developed programme saves the surface images in bmp format and gives the possibility to determine the proposed damage parameter D quantitatively. Such parameter is estimated near the stress concentrator on the area approximately 0.09 mm^2. Damage parameter is equal to the ratio of the surface area with deformation tracks (PSBs) to the total checked surface in the observed spot.

A set of experimental curves that express the dependence of accumulated damage parameter on the number of cycles has been obtained.

As example, the result of fatigue test of D16AT 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. 5). The correlation and regression analysis shows that the results obtained can be approximated by the function $D = 0.0027N^{0.394}$ with determination coefficient $R^2 = 0.7865$.