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ATOMIC FORCE MICROSCOPY INVESTIGATION OF THE D16AT ALLOY DEFORMATION RELIEF

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The possibility of atomic force microscopy application for the investigation of fatigue damage process of aluminum alloy D16AT has been substantiated. It has been shown the possibility of atomic force microscopy application for the analysis of the surface deformation relief, which is formed under cyclic loading. The height of extrusions raising under the cyclic loading can be considered as a quantitative parameter of fatigue damage of structural elements made of alclad aluminum alloys.

Keywords: aviation structures, fatigue, deformation relief, atomic force microscopy, extrusion.

Можливість атомного додатка сили мікроскопії для дослідження втоми ушкоджують процес алюмінієва alloy D16AT був підтверджений. Показано можливість атомного додатка сили мікроскопії для аналізу рельєфу зовнішньої деформації, що формується під циклічним вантаженням. Висота виштовхувань, що піднімають під циклічним вантаженням, може розглядатися як кількісний параметр пошкодження втоми структурних стихій, зроблених з алюмінієвих alloys в алюмінієвій фользі.

Ключові слова: авіаційні структури, втома, рельєф деформації, атомна мікроскопія сили, виштовхування.

Introduction

Fatigue damage analysis of aviation structures becomes more required because of damage tolerance principal is practiced at a large scale in aircraft designing, because of increasing operation time and number of flights during the aircraft life span. At the same time the requirement of minimum mass for aircraft is actual also.

The aluminum alloys like D16AT, V95, 2024 T3, 7075 T6 are widely use for the production of main structural components of the wing, empennage and fuselage of the aircraft.

They are covered by pure aluminum for the corrosion protection.

The deformation relief is formed on the surface of these aluminum alloys under cyclic loading.

Deformation relief is external feature of local micro plastic deformation formed by the dislocation motion and dislocation transformation.

As a result of these we can watch the extrusions, intrusions and persistent slip bands on the surface of material.

The results of deformation relief investigations [1] show that deformation relief parameters (damage parameter *D* and fractal dimension *Dp/s*) have close correlations with cyclic loading and can be used for the models of fatigue life prediction for the structural components and for the aircraft in general. It has been shown [2; 3] the sensitiveness of the deformation relief parameters to the maximum stress level and to the stress ratio.

The main aim of this work is to show the possibility of atomic force microscopy application for the quantitative analysis of the deformation relief formation.

Deformation relief analysis by the light and electron microscopy

The subject of presented investigations is deformation relief which is formed on the surface of alclad aluminum alloy. Deformation relief is formed under cyclic deformation with stress which is corresponded to the elastic deformation of aviation structures in real aircraft operation.

Light microscopy is the reliable and simple methods for the investigation of deformation relief evolution under cyclic loading. Light microscopy gives the possibility to analyze the deformation relief on the mesoscale level [1; 2]. In the presented results we used the VHX Digital Microscope Multiscan KEYENCE (fig. 1). It has a very good separate charge coupled devices (maximum 54 million pixels). The application of light microscope for the analyses of deformation relief gives the possibility not only to learn the relief evolution but also to receive surface topography (fig. 2) near the stress concentrator.

Fig. 1. VHX Digital Microscope Multiscan KEYENCE

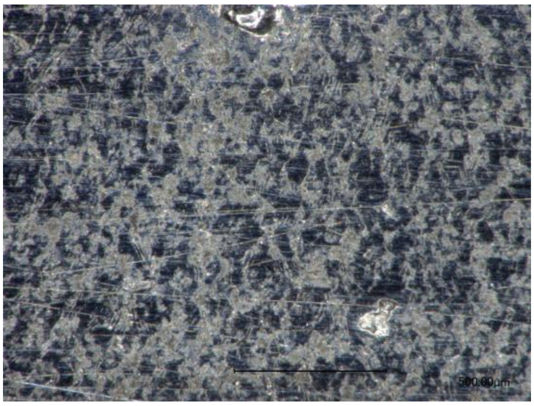


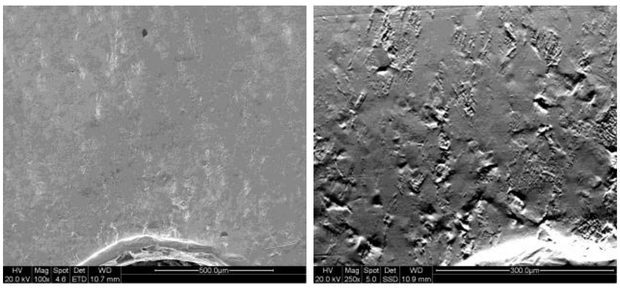
Fig. 2. Deformation relief features near the stress concentrator (hole) after 22 000 cycles, σ_{max} = 234,5 MPa, R = 0.

Quanta 400 Scanning Electron Microscope is used for the investigation of deformation relief morphology, i.e. to reveal the signs of micro plastic deformation on the surface of aluminum alloy.

For the analysis of surface deformation relief by the light microscope it is necessary to polish the specimen surface by diamond paste to receive the roughness no more then 3 micron. After polishing all specimens are washed by ethanol, are dried out and are kept in vacuum. The special features for the scan microscope preparation for the every specimen analysis is a selection of necessary filament voltage to find the best focusing under current emission.

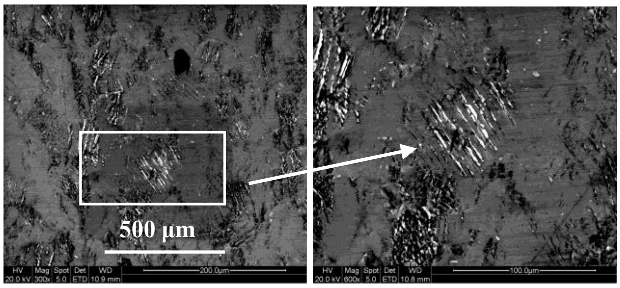
The main parameters of scan microscope work for the investigation of deformation relief are: high voltage 20,0 kV; pressure 3,2 e^{-6} mbar = 3,264 · 10^{-4} Pa; filament current 2,5 A; emission current 103 μA.

The investigation of deformation relief on the surface of alclad aluminum alloy D16AT by the Scanning Electron Microscope allows reveal the main structural formations on the surface namely: extrusions and intrusions in one-way and different-way persistent slip bands direction (fig. 3, 4) and relief clusters without any definitely marked direction (fig. 5) but with some high roughness area and single profile peak like extrusion or nonessential surface resigning/deepening (fig. 6).



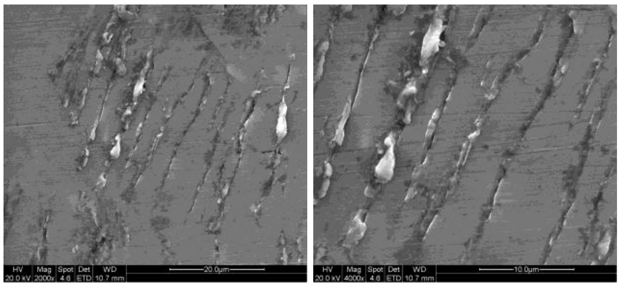
a 100^x *b* 250^x

Fig. 3. Deformation relief images obtained by: *a* — Scanning Electron Microscope; *b* — surface topography near the stress concentrator received by Back Scattered Electron Detector



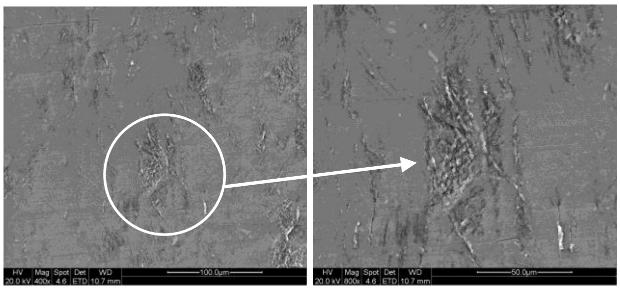
a 300^x *b* 600^x

Fig. 4. Area with the signs of micro plastic deformation at different microscope scales: *a* — 300^x; b — 600^x



a 2000^x *b* 4000^x

Fig. 5. Slip bands image in a grain of polycrystalline aluminum alloy formed on the surface under cyclic loading at different scales: *a* — 2000^x; *b* — 4000^x



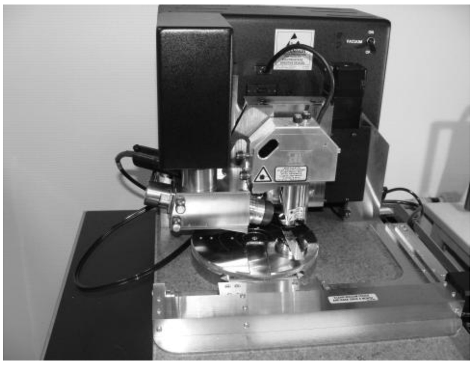
a 400^x *b* 800^x

Fig. 6. Clusters creation with resigning of deformation relief at different microscope scales: *a* — 400^x; *b* — 800^x

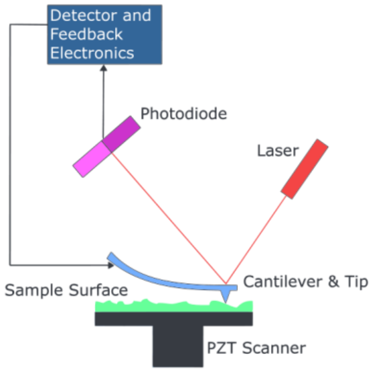
Apparently the deformation relief has an expressed morphology. It determines the possibility and necessity of geometrical characteristic investigation of the deformation relief by the atomic force microscopy.

D16AT alloy deformation relief investigation by the atomic force microscopy

Deformation relief formation and evolution is the process at micro-, meso- and macro scale levels. Atomic force microscopy provides the detail investigation of deformation relief at the micro scale levels [4]. The deformation relief morphology of alclad aluminum alloy D16AT has been investigated by the Dimension™ 3100 Atomic Force Microscope (AFM) (fig. 7). Atomic force microscopy (AFM) is a very high-resolution type of scan probe microscopy with demonstrated resolution on the order of fractions of a nanomoter, more than 1000 times better than the optical diffraction limit.



a



б

Fig. 7. Atomic Force Microscope (*a*) and its main components (*b*)

The Atomic Force Microscope consists of a cantilever with a sharp tip (probe) at its end that is used to scan the specimen surface. The cantilever is typically silicon with a tip radius of curvature on the order of nanometers. When the tip is brought into proximity of a sample surface, forces between the tip and the sample lead to a deflection of the cantilever according to Hooke's law. Depending on the situation, forces that are measured in AFM include mechanical contact force, magnetic forces, etc. Along with force, additional quantities may simultaneously be measured through the use of specialized types of probes. Typically, the deflection is measured using a laser spot reflected from the top surface of the cantilever into an array of photodiodes. Other methods that are used include optical interferometry, capacitive sensing or piezoresistive AFM cantilevers. These cantilevers are fabricated with piezoresistive elements that act as a strain gauge. Using a Wheatstone bridge, strain in the AFM cantilever due to deflection can be measured, but this method is not as sensitive as laser deflection or interferometry.

The measurement of deformation relief by the AFM has been conducted in a few places near the stress concentrator. The dimensions of investigated place are selected due to the relief clusters dimension from 10 till 100 micron; correspond to the one grain size.

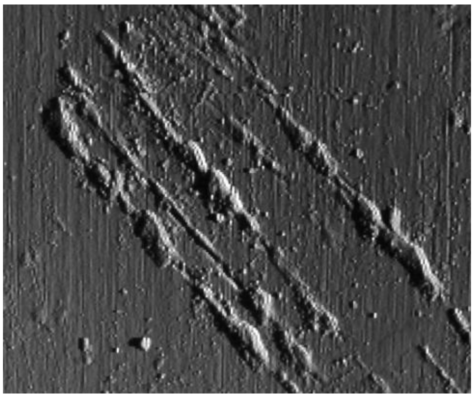
The results of deformation relief investigation by the AFM

The previous optical investigation of surface deformation relief of alcald aluminum alloy D16AT has shown the monotonously evolution of relief under cyclic loading, it is mean that the density of persistent slip bands is grows, and the number of extrusions and intrusions increases as well [2]. The monotonously evolution of deformation relief was observed at the initial stage of fatigue damage. It is proved by the evolution of deformation relief parameters: damage parameter *D* and fractal dimension *Dp*/*s*.

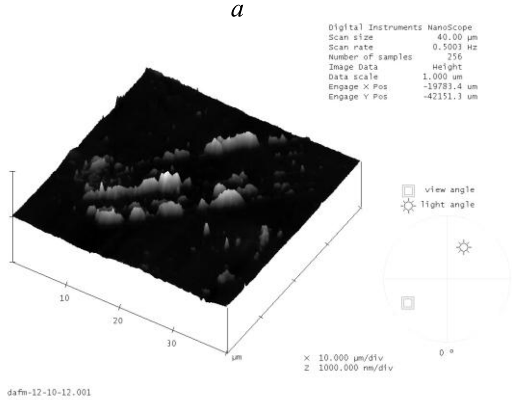
Nevertheless the evolution of this two dimensional characteristics of saturation (damage parameter *D*) and fractal dimension *Dp*/*s* (observed from two dimensional images) demonstrates the presence of saturation stage of both deformation relief parameters. This phenomenon complicates the accumulated fatigue damage analysis by the light microscopy at the stage of crack nucleation.

Exactly this determines the necessity of looking for the additional quantitative relief parameters received by the AFM application for the 3D deformation relief analysis with the monitoring of extrusion height and intrusions depth.

Let's look at the persistent slip bands (fig. 8) on the surface of specimen after 22000 loading cycles under σ_{max} = 234,5 MPa, R = 0.



a



b

Fig. 8. Two dimensional image (*a*) and three dimensional image (*b*) of deformation relief area

The quantitative characteristics of relief are determined by the scanning of selected surface line with the measurement of extremums on profile line. The determination of extrusion height and intrusions depth are conducted by a few scanning lines. As example in the table below one can see the results of measurement of surface profile extremums by three scanning lines.

Evidently from the table after 22000 loading cycles the extrusion height can reach the h_e = = 455,02 nm.

The deformation relief extremums after 22000 loading cycles

Scanning lines	Extrusion height, h'_e nm	Intrusions depth, h'_i nm
1	455,02	67,332
2	276,48	96,79
3	411,46	25,46

The next fatigue loading (which correspond the saturation of two dimensional relief parameters) has shown the continuation of modification and transformation of extrusion/intrusion structures geometry. And after 180000 loading cycles the extrusion height at the same area can reach 1273 nanometers. The extrusion height increment can be 180 % and more.

Conclusions

The AFM can be proposed like an effective instrument method for the quantitative analyses of deformation relief for the determination of accumulated fatigue damage.

Presented results of the investigation of deformation relief morphology under cyclic loading by the AFM gives the ground to suppose that the height of extrusions is grows during all stage before fatigue crack initiating.

The monotonous evolution of extrusion height give the possibility to use this parameter in regression models of fatigue life prediction aviation structures by the deformation relief on the surface of aluminum alloys.

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