OPTICAL TOPOGRAPHY ANALYSIS OF SINGLE CRYSTALS FOR INDIRECT ESTIMATION OF DEFORMATION DAMAGE OF AIRCRAFT ALLOYS UNDER FATIGUE TEST

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ABSTRACT

Single crystal plates were rigidly attached to base specimens of aircraft alloys that undergo fatigue loading. The quantitative and qualitative parameters of a single crystal relief were determined by optical topography analysis. They were found to be dependent indirectly on deformation damage of a base specimen (alloy with complex chemical and phase composition). The different orientations of single crystals were investigated and orientation <100>{100} was shown to be the most sensitive and informative for determination of (a) the number of cycles, (b) stress amplitude and (c) damage localization sites. The quantitative topography analysis of single crystal relief roughness was found to be useful for indirect monitoring the deformation damage and forecasting the level of exhaustion of lifetime of the base specimen.

KEYWORDS

Topography analysis, roughness, evolution, smart sensor, synergetic system

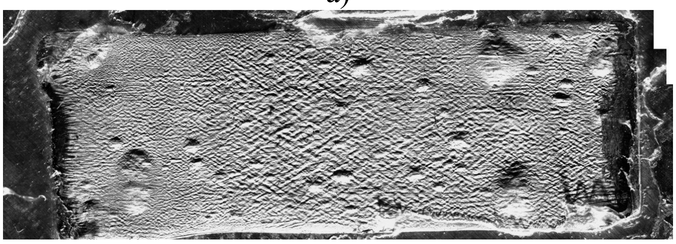
INTRODUCTION

In our previous works we used the single crystal aluminium foils as a detector to analyse deformation pre-history and exhaustion of lifetime resources in aircraft Al-alloy. The information is assumed to be obtained from quantitative characterization of correlation between characteristics of relief and level of lifetime exhaustion in aircraft structures under investigation. We used the methods constructed on the notions of “band” and “band width”, which are not so strong and consistent for the very complex surface profiles observed by us [1,2]. In this work we made the more careful topography analysis of foil surface roughness and derived the more strong classification of surface features.

EXPERIMENTAL

Aluminum single crystals were used as different kinds of materials for sensors. Cylindrical single crystals with diameter of 15 mm were grown by vertical Bridgeman method in a crucible made of yttrium oxide (for aluminum single crystals) from seeds with the required axial orientation. For this purpose high pure aluminum (99.995 wt. % Al) were used. The single crystals grown were cut by means of the special electric erosive device in plates with thickness of 0.4–0.5 mm, length of 30 mm and width of 10 mm with desired crystallographic orientations. Orientations for cutting were defined on the basis of X-ray difractometer with a special portable crystal holder, which can be used with X-ray goniometer, and then in cutting machine. After final polishing the single crystal foils contain (as it was observed by X-ray topography method) characteristic regular defect structure [3-5]. Aluminum sensors with orientations <001>{100}, <111>{110}, <221>{110} were prepared and tested (see Fig. 1). Sample loading with single crystal sensors was carried out with working frequency, which was equal to 11 Hz. The shape of loading cycle is a sinusoidal one with minimal loading value near zero. Attachment method for binding sensors and samples was based on cyanoacrylate adhesive. Optical microscopy was used for investigation of the relief created during mechanical loading of samples with magnification 30 and some increase of this value up to 100 (it was dependent on the relief observed).

a)



b)

Figure 1. The shape of sample and typical orientation of sensor on it (a); increased view on sensor.

DEPENDENCE ON CRYSTALLOGRAPHIC ORIENTATIONS

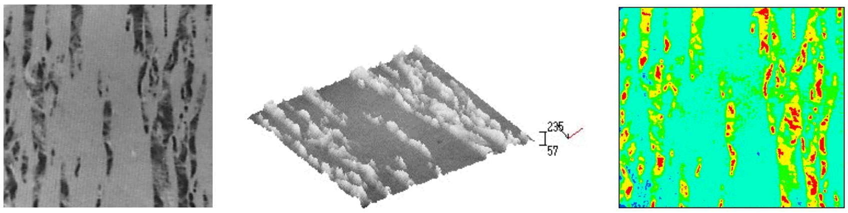
Numerous routines of image acquisition after each stop of testing machine were made by automated methods on the basis of Leica microscope with SONY CCD camera attached to personal computer by video adapter and TCI-Oculus frame-grabber card with storing on hard disk of personal computer.

The simplest ("naive") 3D reconstruction was used on the different levels of black-and-white contrast regions in the photographic images, which was expressed in 256 gray scales. It should be noted that these pseudo-3D reconstructions have only estimation value, because only raster scanning microscopy or true light stereoscopy can give the true 3D picture of the surface pattern with taking into account shading, distortion and diffraction. It should be noted that this pseudo 3D dimensional reconstruction is used only for emphasizing some latent details of sensor relief, which cannot be noted from initial images. The main advantage of 3D reconstruction consists in possibility to derive the most useful and fruitful strategy for qualitative and quantitative description of images with different crystallographic orientations and loading conditions.

As it was mentioned above single crystal plates with different crystallographic orientations were grown and cut for preparation of sensors.

Tension axis <001>

In Fig. 2 the surface relief of single crystal sensor <100>, which was formed after 46000 cycles of fatigue loading, is shown. It is clear, that relief bands are discontinuous, curvilinear and elongated in a tension direction. At the same time dislocation slip in slip planes {111} can lead to creation of relief stairs in the plane under observation {100}, which are tilted at the angle 36° with a sample axis.



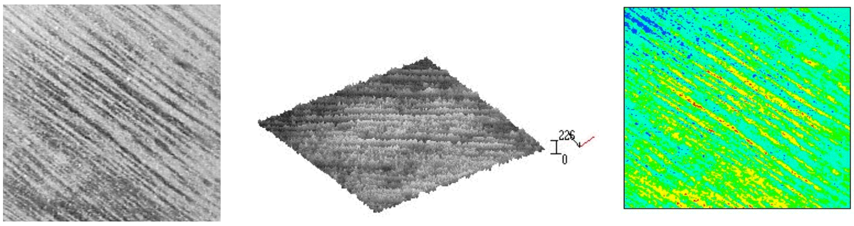
a b c

Figure 2. Surface relief of single crystal sensor <100>, which was formed after 46 000 cycles: a - initial image, b – naïve "three-dimensional reconstruction", c - contour plot.

Crossing lines of slip planes with a plane under observation (plane of sensor) should be continuous and straight. It is obvious, that the surface relief observed by us at the surface <100> was not created by dislocation slip. In contrary, as it was aforementioned it is manifestation of new plasticity mode, namely hydrodynamic flow of material. This plasticity mode is assumed to be promoted by crystalline defect localization in some microscopic volumes with a great extent of disorder in these volumes and appearance of liquid-like regions (non-crystalline phase) [3–5]. In our case for symmetric (in relation to tension axis) orientation of 4 interacting slip system, the relief observed is manifested as a set of cell boundaries (which are morphologically similar to well-known Benar cells observed in an unstable liquid) crossing with the plane under observation {100}. For other crystallographic parameters (without symmetric orientations) of loading traces of hydrodynamic flow of material can be presented by a straight band pattern relief (shear bands, persistent slip bands, etc [6–9]), oriented in the directions of maximal tangential stresses.

Tension axis <221>

In a sensor with orientation <221> during fatigue tests for stress levels, which are slightly higher than elasticity limit of sensor material, sensor surface will contain a set of thin lines (Fig.3) — slip traces corresponding to crossing lines of the primary slip plane {111} with plane {110}. The increase of the applied stress leads to impeding dislocation slip in a primary slip {111}, because of interaction between nonparallel gliding dislocations in two directions <110> and creation of obstacles (barriers). Further fatigue loading will lead to blockage of the primary slip system and defect accumulation in layers nearly parallel to the primary slip plane {111}. Thus appropriate conditions for transformation of these layers in traces of liquid-like channels can appear and the further deformation will be created by hydrodynamic flow in them. In fact, we deal with the so-called persistent slip bands, which are typical for surface relief created during fatigue tests. Unfortunately, despite of numerous attempts [10, 11] up to the recent times this type of band pattern could not be described satisfactorily. Finally, sensors with orientation <221> are very promising for investigations in the wide range of loading conditions.



a b c

Figure 3. Surface relief of single crystal sensor <221>, which was formed after 90 000 cycles: a - initial image, b - naïve "three-dimensional reconstruction", c - contour plot.

According to the results aforementioned the different ways of analysis have to be applied for processing surface patterns with different sensor orientations. Their analysis allows to derive the following conclusions.

- Sensitivity of sensors to deformation damage of samples made on the basis of aircraft alloys is defined by their orientation.

- Sensors with orientation <001>{100} and intensive symmetric dislocation slip are the most sensitive ones in relation to deformation of sample. In these sensors non-crystallographic deformation relief forms in the very beginning of loading and it undergoes significant changes during the further loading cycles. They are suitable for forecasting critical states and durability of constructions from aircraft materials.

- Sensors with orientations <221>{110} are useful for investigations of quantitative parameters of correlation between characteristics of surface relief and life time of constructions or samples under load.

The significant problems with determination of identification marks of fatigue relief by well-developed methods of band density, periodogram and spectra analysis for heterogeneous media are caused by intrinsic geometrical features of the relief observed.

Firstly, surface relief has three-dimensional structure and the same spectrum characteristics obtained for its projection in plane can be prescribed for different types of relief with the same projections.

Secondly, it is situated on several scales and cannot be satisfactorily characterized by the limited number of scale parameters as periods or other spectra characteristics.

Thirdly, surface relief has dynamic nature, i.e. it gradually changes its morphology with increase of loading conditions (for example, number of cycles or stress amplitude).

That is why for full characterization of surface relief one need to derive some universal characteristics for three-dimensional figure, its two-dimensional projections in plane and for several scales for the same time. This task can be fulfilled on the basis of the notions of self-similarity and fractal geometry. It should be noted that all results, which are considered below, are obtained for the very simplified method of 3D reconstruction (as it was aforementioned) with subsequent cross-sections by planes, which are perpendicular to the sensor plane. The more sophisticated scanning equipment is necessary for more careful investigation of 3D peculiarities of sensor surface relief.

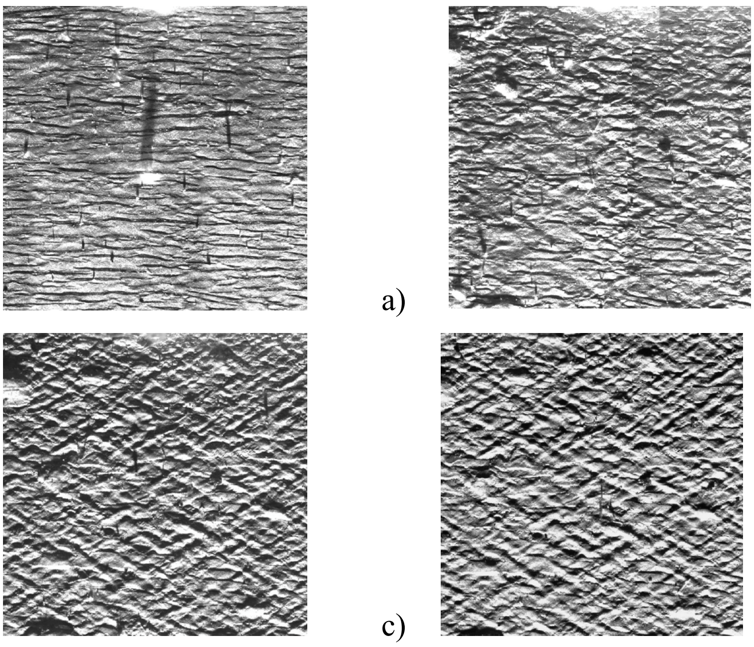
CLASSIFICATION OF STRUCTURAL PRIMITIVES ON SENSOR SURFACE

Qualitative method of sensor surface topography analysis consists in elaborating the classification of structural primitives which appearance and evolution can be observed due to light microscopy. From the very first glance one can easily note the evolution marks in development of sensor surface relief (Fig. 4). The main peculiarity consists in that evolution patterns are gradually varied for different numbers of fatigue cycles and stress values.

According to our observation we propose the following classification scheme for the main qualitative signs of sensor surface evolution.

1. High-contrast horizontal flat band-like pattern ('flat bands').
2. Low-contrast shadow pattern created by small ellipsoidal horizontal extrusions ('hills').
3. Appearance and gradual growth of big solitary nearly equiaxial extrusions ('blisters').
4. Appearance of merging and coalescing 'hills' with creation of the larger hills ('ridges') inclined to the tension axis (angles are nearly equal to ±34–38°).
5. Creation of the whole net of 'ridges' — 'highlands'.

Analyzing these results we derive the following persistent consequence of stages along with the increase of the number of cycles: 'flat bands' ⇨ 'hills' ⇨ 'blisters' ⇨ 'ridges' ⇨ 'highlands'. Here, 'blisters' can be manifestation of heterogeneity of defect substructure formation in sensor and sometimes can be absent.



a) b) c) d)

Fig. 4. Typical panoramic views for 146 MPa: a) 96,000; b) 270,000; c) 750,000; d) 970,000.

On the basis of the elementary structural notions we created database of standard patterns, correspondent numbers of cycles and stresses, form-factors of specimens and sensors. In fact, we obtained a large volume of data classified not only by sensor location, identification number of specimen, stress level, numbers of cycles, but also by many scales of calculation. We found an analogy with everyday situation when in ordinary business environment one have to process data on multiscales: time (day, month, year), position (region, city, state, continent, etc), volume (item, box, car container, etc.). Because of the huge volume of the data (images scanned, panoramas merged, standard patterns, geometric primitives obtained) we tried to store, organise and manage them due to available technology of 'multidimensional cubes of data' in the framework of the available software for OLAP-processing (Oracle Express Server 6.02).

As a result of this 'data mining' analysis we derived the persistent pre-emptive tendency for initiation ranges of evolution stages along with the increase of the number of cycles for different stress levels (Fig. 5).

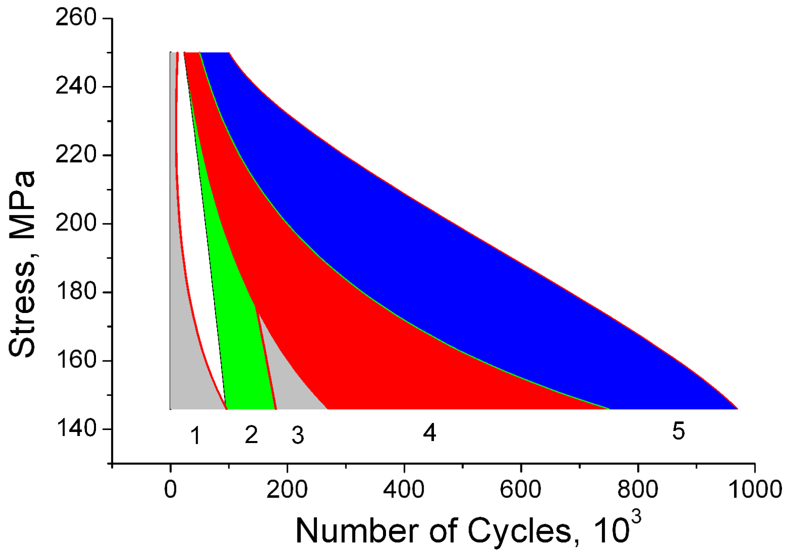


Fig. 5. Persistent consequence for initiation ranges of evolution stages along with the increase of the number of cycles for different stress levels: 1 — 'flat bands', 2 — 'hills', 3 — 'blisters', 4 — 'ridges' and 5 —'highlands'.

SYNERGETIC DIAGNOSTIC TECHNIQUE: SMART SENSOR + EXPERT SYSTEM

On the basis of the very sensitive behavior of sensor surface to loading conditions (strain localization, stress, number of cycles, etc.) we propose to design the synergetic diagnostic technique on the basis of smart sensor system for large-scale data processing [12]. It allows us not only monitor some critical events (overload, abrupt exhaustion of exploitation resource) in solitary parts of construction, but obtain some cooperative effect based on aggregation of results from many smart sensors situated in different parts of constructions also.

Now we elaborate the basic set of standard patterns of sensor surface for different fatigue loading conditions that allowed us to apply automatic image analysis and decision support system (Fig. 6). In addition to permanent evolution on computer hardware and decrease of their prices we were happy to make progress from high-cost desktop system (PC coupled by special adapter with industrial CCD-camera and microscope) to relatively low-cost and simple mobile system (notebook connected by standard USB-port with cheap and powerful web-camera with CCD-chip).

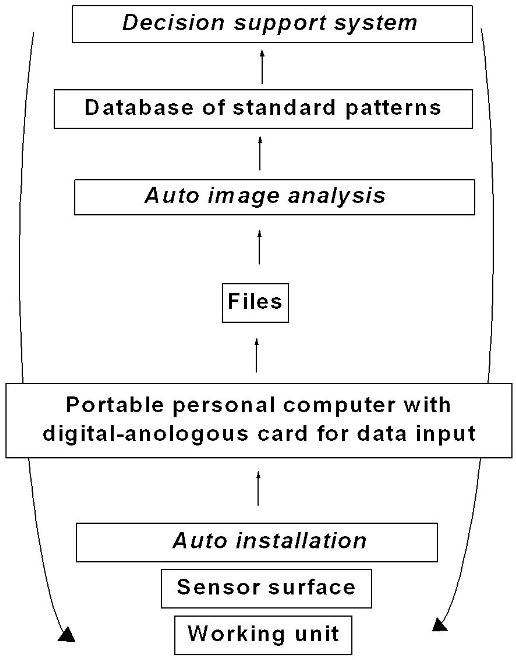


Fig. 6. Online schema of data capturing and processing by means of the enhanced method: wearable capturing system and decision support system on the basis of automatic quantitative analysis.

It is quite easy to see that forthcoming progress in hardware and software can easily allow us to simplify this equipment to the mobile system with wireless delivery of data to data processing center on the basis of a mobile phone with web-camera, palm-PC with web-camera, smart card with embedded micro camera, etc.

The improvements aforementioned will allow us not only monitor some critical events (overload, abrupt exhaustion of exploitation resource) in solitary parts of constructions, but also create the cumulative representation of the whole behavior of constructions in complex intelligent systems. On the very first stage we constructed the virtual reality model of sensor surface evolution on the basis the simplest geometric primitives that are available in virtual reality modeling language (VRML) [13]. It describes schematically the complex specimen under current investigation with two sensors attached to face and flank sides (in the right part) and the correspondent contour maps (in the left part) of multiscaling parameter that characterizes the sensor surface evolution.

This model allows us to bring to light the complicated nature of sensor surface evolution by simultaneous comparison of two evolving patterns. In general, we see that usage of the more sophisticated schemes of sensor locations on industrial constructions with correspondent virtual models will give us the more valuable (i.e. synergetic) information on their fatigue damage.

CONCLUSIONS

Finally, we can conclude that for estimation of the concrete correlation between sensor surface relief and changing fatigue conditions should be calculated on the basis of sensors with different orientations. For this purpose different quantitative approaches can be used, but the more reliable and consistent one is based on orientation <001>{100}.

The sensor surface evolution has tendency to evolve for the higher values of number of cycles and stress amplitudes, but the precise measure of this phenomenon should be discovered by the quantitative analysis [4,5]. Nevertheless, now for practical purposes we would like to propose the idea about elaboration of automatic software expert system on the basis of the elementary structural notions proposed. For this purpose, qualitative marks can be systemized on the basis of the following structural primitives: 'flat bands', 'hills', 'blisters', 'ridges', 'highlands', etc. But the strict rules should be applied for the intensity, incidence angle and other illumination conditions. Because of the very complicated nature of the observed structural primitives we cannot use directly the standard software on the basis of ordinary geometric primitives (lines, angles, rectangles, circles, etc.) and develop on its basis some automation routines. It was useful only for calibration needs and cannot help in the characterization of some projections of the 3D surface. For this purpose one should restore the real shape of sensor relief in 3D embedding space. But nevertheless we were happy to create the qualitatively different classification of 2D images and its quantitative description can be improved.

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