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Evolution of the Deformation Relief on the Surface of a Clad Aluminum Alloy at Random Cyclic Loads

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Abstract. *The deformation relief was revealed to be formed and evolved on the surface of a cladding layer of a D16AT aluminum alloy under random cyclic loading. The surface saturation, roughness, and microplastic deformation are found to be quantitative estimates of the deformation relief and damage levels. Experimental deformation relief characteristics-load cycle number relations are similar and can be employed for predicting the fatigue crack initiation in aircraft structure elements.*

Introduction.

Recent research and development efforts in the field of new nondestructive inspection methods create the basis for Structural Health Monitoring systems providing continuous aircraft damage monitoring.

Fatigue sensors [1-3] perform the function of monitoring the exhaustion of carrying capacity of structures under cyclic loading. Such sensors are built in or fixed on structure elements and respond to in-service loads. The sensor response to the variation of structure loads provides a means of estimating the damage level and predicting their residual fatigue life.

The development of sensors offers promise of their employment as diagnostic tools of fatigue damage accumulation through the deformation relief (DR) on the surface of easily deformable pure aluminium [4].

These sensors can be monocrystalline in the form of thin films from aluminum single crystals [5], or polycrystalline as a specially treated surface of the cladding layer from aluminum of commercial purity on the specimens from structural aluminum alloys [4, 6].

The loading history for such sensors is estimated by the time variation of surface DR characteristics.

It may be the DR saturation D [7] or its fractal dimension [8]. These parameters are determined automatically from the surface images with local microplastic deformation traces.

These 2D images are obtained using optical microscopes (x 200-400) fitted with a digital camera[6-9] (Fig. 1. a-c). The DR saturation is also assessed with other effective methods based on automatic analysis of digital images [4, 10].

The surface DR as a diagnostic tool of fatigue damage becomes more informative with its 3D representation (Fig. 1. d-f). Micron-Alpha noncontact interference profilometer permits of determining additional DR characteristics (3D numerical data), which cannot be identified from optical 2D images. They are the relative roughness of the surface relief $\bar{R}_a$ and microplastic surface strain ε_a [11].

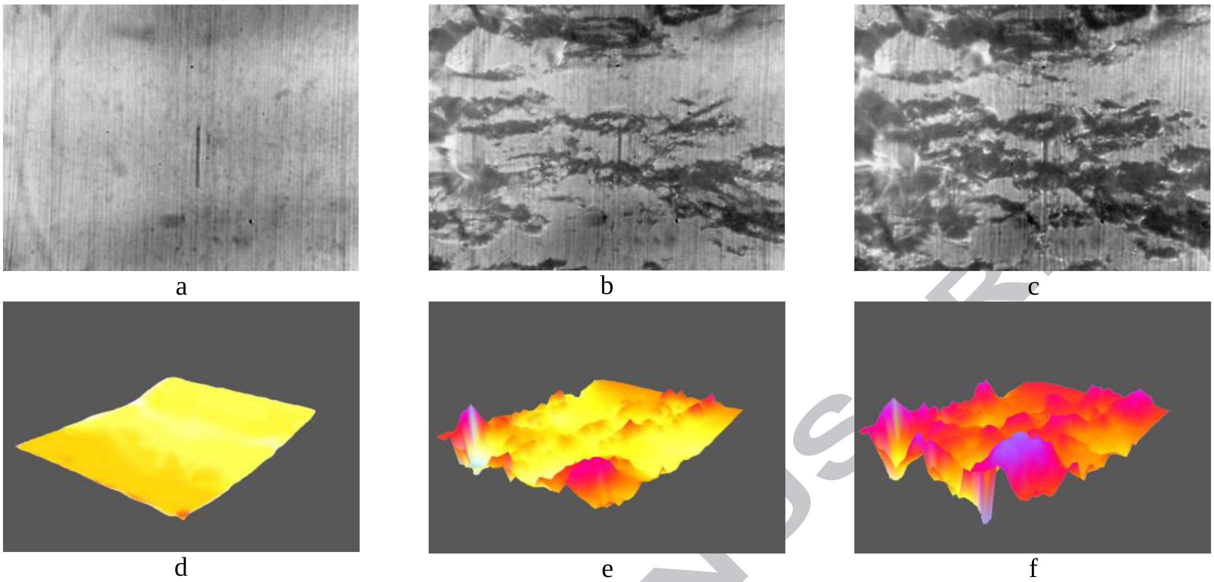


Fig.1. DR Evolution monitoring by optical microscopes (a-c) and Micron-Alpha noncontact interference profilometer (d-f), where (a) and (d) are surface initial conditions, (b) and (e) are intermediate, (c) and (f) are before crack initiation

The interrelation between these DR characteristics and its saturation D was studied under regular cyclic loading of the specimens from a D16AT aluminium alloy with a thin cladding layer [11]. The parameters D, $\Delta\bar{R}_a$, and ε_a were established to increase with the number of cycles, while their growth rate is dependent on the cycle stress. The fatigue crack initiation takes place when those parameters reach their limiting values D^*, ε_a^*, and $\Delta\bar{R}_a^*$. These values are invariant under the cycle stress, thus, they can be used as the criteria of the limiting state, viz. the initiation of a fatigue crack in clad aluminum alloys.

The present study is devoted to the behaviour of the DR characteristics at random cyclic loads close to the in-service range for aircraft structures.

Materials and Methods.

Flat specimens from a structural D16AT aluminum alloy, coated with a cladding layer from technical purity aluminum 50 µm thick, were tested. The manufacturing procedure provides the joint rolling of D16 alloy itself and pure aluminium foil. The clad layer is weakest and sensitive, but inseparable part of tested specimens and serves as indicator of the accumulated damage.

Clad layer chemical composition:

1) impurities (not more): iron - 0.3%, cupper - 0.02%, manganese - 0.025%, zinc - 0.1%, titanium- 0.15%, magnesium - 0.05%;

2) aluminum (not less) - 99.3%.

Core material (D16) chemical composition:

1) impurities: silicon - 0.5%, iron - 0.5%, cupper - 3.8%, manganese - 0.3%, magnesium - 1.2%, chrome - 0.1%, zinc - 0.25, titanium - 0.15%.

2) aluminum - other.

In the central portion of the specimens 4-mm diameter holes were drilled to provide the stress concentrators for the localized crack initiation (Fig. 2). The size of hole was selected taking in consideration the typical dimensions of the rivets in aircraft structures. The specimen surface portion adjacent to the hole was polished with diamond paste.

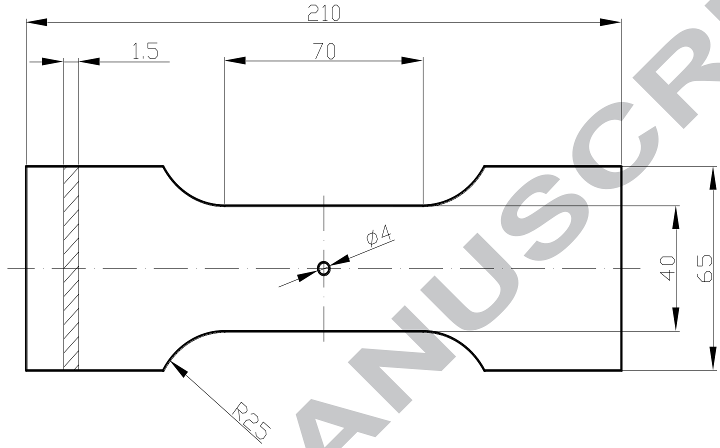


Fig. 2. Fatigue test specimen

The specimens were cyclically loaded on a BISS Bi00-202V servo hydraulic machine using a MiniTWIST standard quasi-random test program [12] for aircraft wing. This standardized program includes high level loads.

The program combines the random alternation of load cycles within the block and cyclic repetition of the identical blocks. The ratio σ_a/σ_m is the cyclic loading parameter, where σ_a is the random cycle stress amplitude (cycles with $\sigma_a \geq 0$) and σ_m is the mean cycle stress (Fig.3).

The loading intensity of the flight simulated with the program was controlled by the ratio σ_a/σ_m, which was reduced to the ten types, from 0.222 to 1.6. One block corresponds to 4000 flights of different loading intensity. The number of flights (cycles) was taken as the fatigue life characteristic.

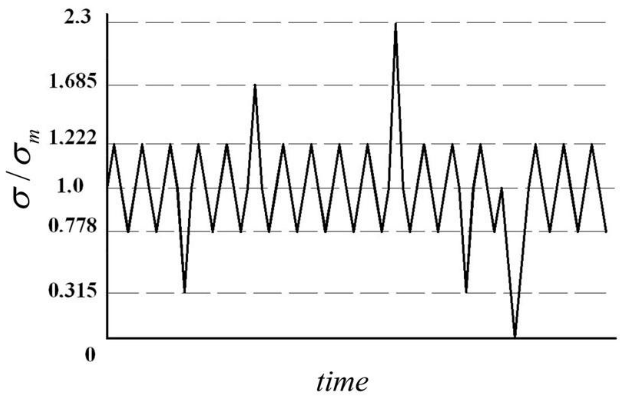


Fig.3. The fragment of a random loading block

The specimens were tested at the three σ_m levels: 100, 90, and 80 MPa. The load rate was 75 kN/s.

Under cyclic loading, DR of a cladding layer was monitored at regular intervals with Micron-alpha optical interference profilometer on a 225x170-μm surface site adjacent to the hole in the region of stress concentrations. Principle of 3D deformation relief measurement of Micron-alpha profilometer is based on wavelength of simple light usage and is independent from light source settings. The 2D deformation relief measurement was carried under the same light conditions that were monitored on standard sample and controlled by digital image analyses.

Each specimen possessed four test sites, at both sides of the specimen and at both sides of the hole. The number of measurements was in the range from 4 to 8 depending on the surface state (for example local scratch, inclusions, etc.). First results for those sites were averaged.

Cyclic loading was accomplished till the moment of initiation of a fatigue crack 0.5 mm long on those sites.

The surface image with DR traces was digitally processed, and 3D topography of an examined surface was determined [11].

The DR surface saturation, roughness, and microplastic deformation of examined sites were evaluated.

The process of plastic deformation in clad layer occurs in the rate exceeding that in the D16 core material. Discussed parameters, including micro plastic deformation have been selected due to the good correlation with the accumulated damage as it was proved by the experiments presented in the works [11].

The DR saturation was quantitatively estimated by the formula

$$D = \frac{S}{A}, \qquad (1)$$

where S is the total area with DR traces on an examined site of the surface area A.

The DR in the direction normal to the surface was quantitatively characterized by the roughness R_a equal to the averaged deviation of absolute surface profile values from the medial line. Surface roughness near areas under cyclic loading was described by a relative R_a ($\Delta\bar{R}_a$) increment [11]

$$\Delta\bar{R}_a = \frac{R_{aN} - R_{a0}}{R_{a0}}, \qquad (2)$$

where R_{a0} is the roughness before loading (initial roughness) and R_{aN} is the roughness after N load cycles.

The DR evolution in 3D leads to an increase in the surface area

$$\Delta A = A_N - A_0, \qquad (3)$$

where A_0 is the surface area before loading and A_N is the surface area after N load cycles.

The procedure of determining the surface area variations by the measurement results of its 3D topography is presented in the study [11].

The microplastic deformation is a quantitative estimate of surface area variations

$$\varepsilon_a = \frac{\Delta A}{A_0} \,. \qquad (4)$$

Results and Discussion.

Under random cyclic loading, the initiation and evolution of local microplastic deformation on the surface of a cladding layer occur from the very first load cycles. As the surface is saturated with DR traces, the rate of change of D, $\Delta\overline{R}_a$, and ε_a decreases (Fig.4). This stage of the DR evolution may be considered the stabilization of microplastic deformation.

The mean stress exerts significant influence on the DR formation and evolution. Thus, the saturation value D=0.15 at σ_m = 80 and 100 MPa is reached after about $N = 3 \cdot 10^4$ and $5 \cdot 10^3$ load cycles, respectively (Fig.4 a,b). This level influences similarly the $\Delta\overline{R}_a$ and ε_a behaviour (Fig.4 c-f).

A decrease in the rate of change of the DR characteristics with the number of load cycles suggests that the initiation of a fatigue crack is preceded by the period of the surface saturation with DR traces.

In this connection, experimental results were presented as the DR characteristics against the relative number of load cycles $\overline{N} = N / N_f$, where N is the current number of cycles and N_f is the number of load cycles to the initiation of a crack 0.5 mm long over an examined site of the specimen (Fig.4).

The points for all examined DR characteristics plotted in the double logarithmical coordinates are shown to be clustered along the straight lines (Fig.5).

The variation of the DR characteristics with a relative number of cycles in the considered range of loads is practically independent of the stress σ_m. It suggests the fact that under random cyclic loading, the DR evolution at different stresses is similar, and its characteristics belong to the defining criteria of the fatigue fracture initiation. As is shown by the data obtained, the relations of the DR characteristics *vs* relative number of cycles are approximated by the exponential functions

$$D = 0.39\,\overline{N}^{\,0.48} \qquad (5)$$

$$\Delta\overline{R}_a = 13.8\overline{N}^{0.53} \qquad (6)$$

$$\varepsilon_a = 0.036\overline{N}^{0.68} \qquad (7)$$

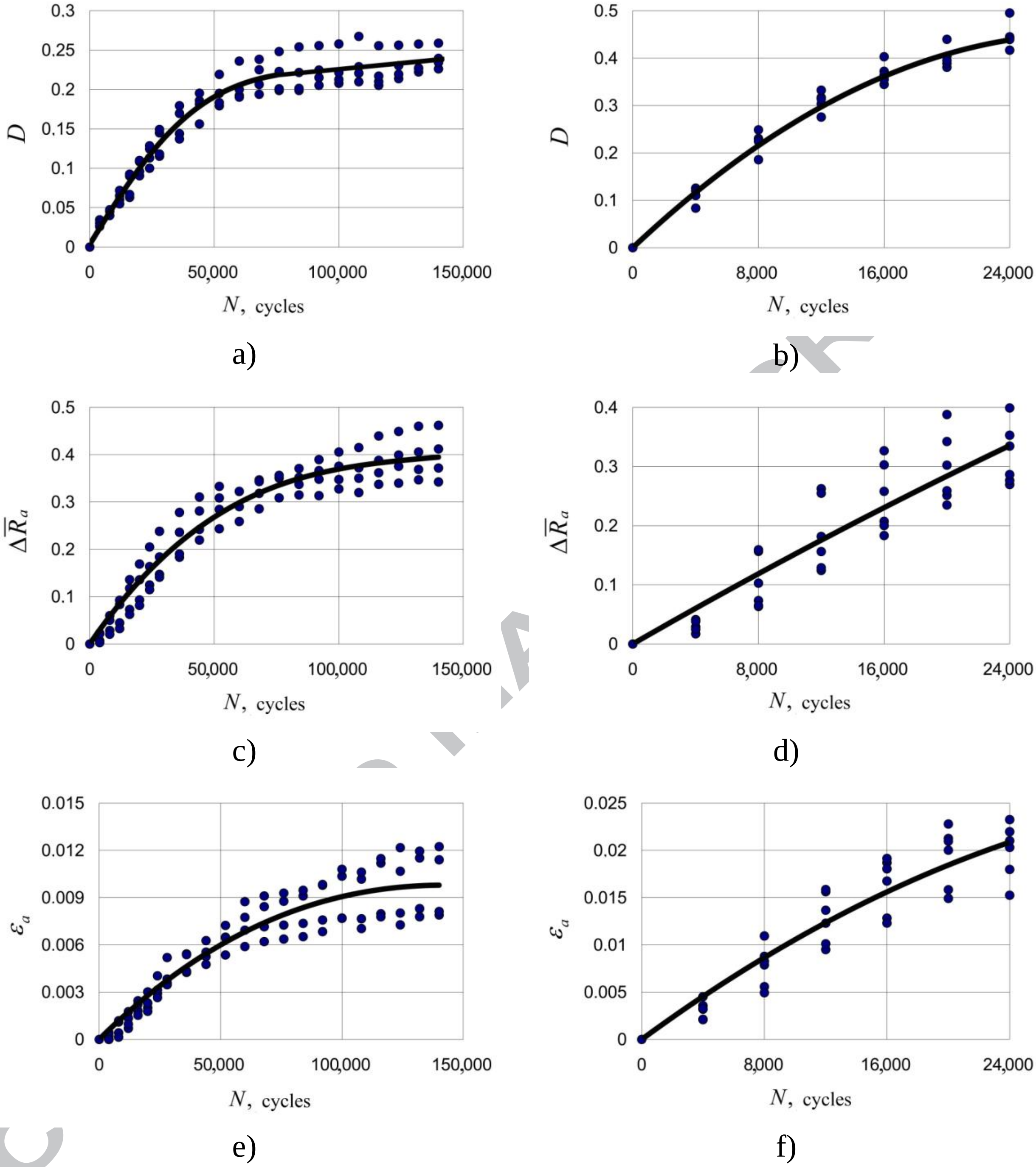
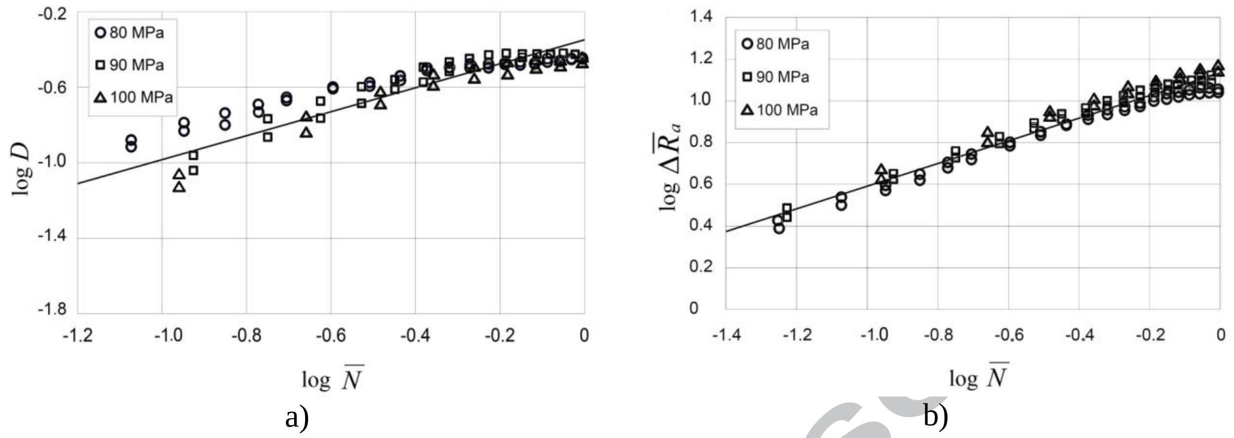


Fig.4. The surface DR saturation (a,b), its roughness (c,d), and microplastic deformation (e,f) vs the number of load cycles for a set of specimens at the two σ_m values: 80 MPa (a,c,e) and 100 MPa (b,d,f).

These relations reflect common nature of the phenomenon: all parameters' evolution determined by the microplastic deformation of the surface layer and correspondent surface area increment.

In accordance with formulae (5) – (7), the crack $(N \to 1)$ is initiated at the averaged limiting values $D^* \cong 0.4$, $\Delta\bar{R}_a^* \cong 14.0$, and $\varepsilon_a^* \cong 0.035$, irrespective of cycle stresses.

As was previously established, under regular asymmetric cyclic loading (stress ratio R=0), $\Delta\bar{R}_a$ and ε_a variations with the relative number of cycles are dependent on the maximum cycle stresses $\sigma_{\max}$ [11]. The limiting $\Delta\bar{R}_a^*$ and ε_a^* values under regular cyclic loading are also dependent on $\sigma_{\max}$.



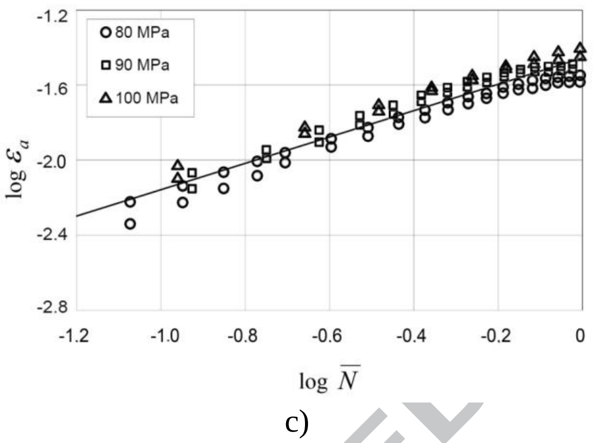


Fig.5. The surface DR saturation (a), roughness increment (b), and microplastic deformation (c) *vs* relative number of cycles to the crack initiation at different σ_m stresses at both sides of the specimens.

Being the invariant to the load level (in the considered load range) the points location reflects the scatter of the result.

Comparison of experimental data by the limiting $\Delta\bar{R}_a^*$ and ε_a^* values at regular and random load modes demonstrates that the points corresponding to different stresses are clustered along the approximation line (Fig.6), related as

$$\varepsilon_a^* = 2{,}9 \cdot 10^{-3} \Delta\bar{R}_a^*. \quad (8)$$

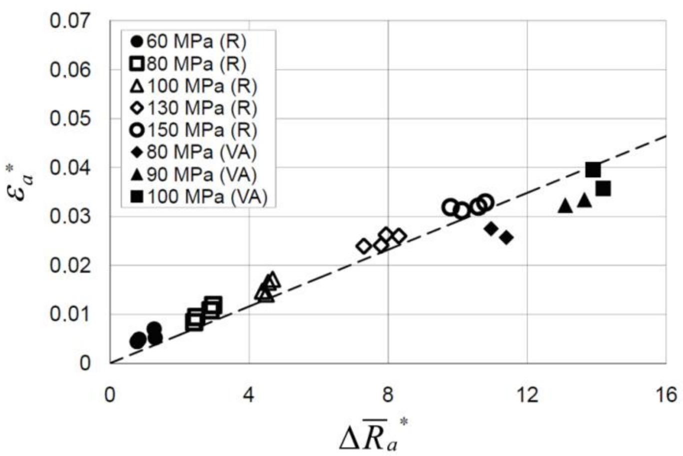


Fig.6. Correlation between the limiting values of microplastic deformation and relative roughness for regular and random loading mode sat different cycle stresses. The dashed line is the approximation of experimental data with Eq. (8).

As follows from the results, irrespective of a cyclic load mode (regular or random)and cycle stresses, the crack initiation results in practically identical correlation between the limiting ε_a^* and $\Delta\bar{R}_a^*$ values for the surface of cladding layer. Relation (8) is invariant under a cyclic load mode and loading level.

The variation of the DR saturation under random loading for examined mean cycle stress levels with the relative number of cycles is described by generalized regression function (5). A similar relation for regular cyclic loading is also invariant under different stresses and is of the form $D = 0.39\,\bar{N}^{\,0.8}$ [11]. It should be noted that the limiting DR saturation values at the initiation of a fatigue crack ($\bar{N} \to 1$) are close for both cyclic load modes ($D^* \cong 0.4$).

However, under random loading, the DR saturation evolves with a higher rate at the initial stage and during the whole period to the crack initiation exceeds similar D values under regular loading (Fig.7).

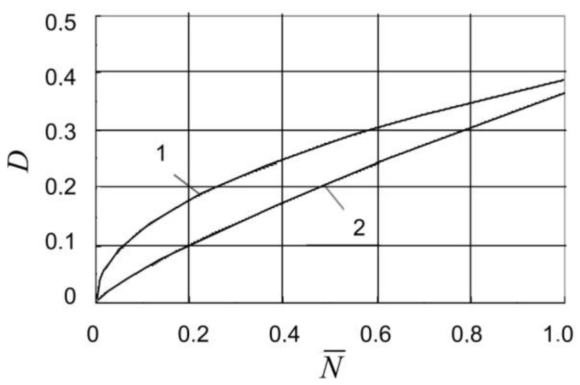


Fig.7. Variation of the DR saturation with the relative number of cycles to the crack initiation at random (1) and regular (2) cyclic load modes.

Thus, it was experimentally established that the DR evolution at random and regular cyclic load modes with the account of crack initiation was an automodelling process. An increase in the DR saturation with the number of cycles depends on the stress levels, *viz.* the larger the stress, the more intensive the DR evolution. The process is considered to be automodelling due to the similarity between the limiting values of plastic deformation and relative roughness under the regular and random loading.

However, if those relations are reduced to the relative number of cycles with the account of the initial fracture stage (durability to the initiation of a fatigue crack), a single relation, common for all stresses is derived. The *D* behaviour for regular and random load modes is different, but its limiting value, corresponding to the crack initiation, is common and equal to about 0.4, irrespective of the mode.

The relation between the DR evolution parameters in the direction normal to the surface ($\Delta\bar{R}_a$ and ε_a) and the number of cycles are also similar under random loading. This behaviour of the above parameters does not extend to regular cyclic loading wherein those relations are effected by stress levels. However, the limiting $\Delta\bar{R}_a^*$ and ε_a^* values at the crack initiation are related by Eq.(8) for both load modes, which is indicative of the general deformation behaviour of the cladding layer surface and its fracture .

Considering that the procedure for measuring the DR saturation is more straightforward as compared to those for roughness and microplastic deformation, the parameter *D* may be used as the basic diagnostic tool for the assessment of fatigue damage accumulation to solve the problems of predicting the number of cycles to the fatigue crack initiation in aircraft structures from a D16AT alloy.

Conclusion.

The deformation relief is established to build up and evolve on the surface of a cladding layer of a D16AT alloy under random cyclic loading. The surface area with DR traces expands with the number of load cycles, accompanied by an increase in roughness. Such a process leads to the evolution of microplastic deformation.

The experimental data demonstrate that the relations of the DR saturation, roughness, and microplastic deformation of the cladding layer surface against the number of load cycles are similar, and with the account of the number of cycles to the fatigue crack initiation, are described by the stress-independent equations.

An increase in the DR saturation under random and regular cyclic loadings is an automodelling process.

At the above load modes the fatigue crack initiation corresponds to the DR saturation plateau ($D^* \cong 0{,}4$) and does not depend on the stress level.

The initiation of a fatigue crack is also consistent with the limiting values of microplastic deformation and relative roughness. For random and regular cyclic loadings, the relation between the limiting values of those DR characteristics is invariant under the cycle stresses.

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Highlights

1. Process of microplasctic deformation on the surface of clad aluminum alloy is used as indicator of accumulated damage under cyclic loads.
2. Deformation relief is described by 2D (deformation relief saturation) and 3D (surface roughness and microplastic surface strain) parameters.
3. Changes of different deformation relief parameters at random cyclic loads are studied and compared between each other.
4. The experimental data at random and regular cyclic loads are compared.