THE FATIGUE DAMAGE OF CONSTRUCTION MATERIALS

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ABSTRACT

Construction material's fractures are due to various imperfections. In a real material there are different types of micro-imperfections. They form an intricate potential relief, which moves in space of material under random fatigue loading [1-3]. As a result material becomes more harder or more looser. The physical model of how it occurs is the main object of this poster. We have found the common law ruled the migration of complex of defects and used the full orthonormal set of functions $\{\varphi_n, 1\}$ *which are the state functions of the operator of "age" [4]. It gives us opportunity to create the new way of fatigue damage analysis of construction materials.*

KEYWORDS

Fatigue damage, sensors, quantitative model, time series, monitoring

INTRODUCTION

The damage of construction material (CM) units which undergo repetitive or random loads relates to fatigue. But up to recent time neither a quantitative model of the initial stage of material fatigue damage nor reliable sensors to record it have been developed. It is connected with the fact that damage is not formed by a single defect but a complex of defects which are generated by random loads, migrate and gather in material of construction forming unordered structures preceding the damage. The duration of process, measured by the number N – cycles of loading (when the forming of cracks is held and the 1st stage of their growth is realized) is compared with the duration of processes on the second stage (the growth of macroscopic cracks).The features of structure of polycrystal alloys are reflected on the structures of their potential reliefs that are originated by both a residual deformation and an imposed fatigue deformation. In local regions of polycrystal material (PM) which undergoes fatigue loads a wide spectrum of strongly exited states arises [3]. These states can not be described by traditional methods of a perturbation theory. With the help of mechanics methods of damage one can study only the growth of macroscopic cracks (second stage) using empirical – formula dependencies describing the growth of a crack.

Contrary to the traditional methods of damage mechanics we use both the methods of theory of chaos and one dimensional time series that are formed by suitable experimental data [3,4]. It permits us to model the features of structure of potential relief of a construction material (CM) and to study its transformation under imposed both the selected single deformation and a fatigue in limit cycle regime.

Objects under study are Aluminum alloy's samples with the SEs rigidly installed on them. *The same spectrum of deformation imposed on both of them.*

Aluminum alloy's samples. Brittle and hard inter-metal combinations originate in Aluminum alloys. The fastness of aluminum alloys (for example, AlCuMg) are raised after its quenching. Selected alloys of Aluminum consist of various types of grains: Al_2Cu – in Al&Cu alloy ; Al_3Fe – in Al&Fe alloy; Mg_2Si, $MgZn_2$ and Cu_2NiAl_7 in multi-compound alloys of Aluminum. These hard fine grains, taking place in a relative soft base material, implement the high resistance to wear of a material. The plastic CMs possess ample types of local structures which readily rearranged to each other at the local zones. Whereas a brittle CMs possess only a single local structure. A lattice can not be rearranged under cycles loading so there is a cracking process. As an example, pure NiTi possess closely adjacent B2 structure and B19 structure which readily rearranged to each other at the local zones. As a result pure NiTi is perfect plasticity material. But NiTi<Fe> becomes a brittle material possessing very stable B2 structure. Below we will present the experimental way of describing these alloys. The various impurities in Aluminum implement the various resistance to fatigue of an Aluminum alloy's samples. The same situation one has in heterogeneous materials, that are used to form the sensitive elements (SEs) for fatigue gages [1]. Further we will also deal with the fatigue features of a SEs, which have a various impurities.

The SE has small weight (no more than 5g) and either 3D or film geometry. They are produced either by the method of powder metallurgy (cold pressing with the subsequent agglomeration in a quartz ampoule) or by thermal vacuum evaporation of the charge onto the polyamide support. The charge consists of a finely dispersed mixture of various initial components, e.g., a mixture of granular $Bi_{2-x}Te_{3+x}$ and $Sb_{2-y}Te_{3+y}$ with carbonyl iron. The fatigue processes in the selected SEs as well as in Aluminum alloys are sensitive to vary impurities and are similar to each other. It gives one the opportunity to develop different type of the SEs for adaptive forecast of fatigue damage of the CMs, subjected to random loads.

Simple model of SE . Resistance, R_{eff}, of SE is simulated by lattice at the corners of which randomly located resistance - $\mathbf{r_i}$ (i = 1,2,3,..., K ; K - total number of grains [or clusters] of SEs). $\mathbf{r_i}$ is the resistance of the grains of the SEs randomly connected with neighboring grains. In that model lattice one may find a simple module in Fig.1 Model lattice consists of L modules, of this kind , each having index - k, (k = 1,2,...., L). At equilibrium state the effective resistance R [**a-b**] = R_{eff} of such module is independent on the value of resistance $\mathbf{r_5}$ = R[**γ-δ**], intervened between γ and δ points (Fig.1). The electric balance is disturbed under loading cycle (irreversible) of deformation. So, R[**a-b**] varies according to quantity of resistance $\mathbf{r_5}$ = R[**γ-δ**]. It is the simplest model of high sensitivity of SEs [1].

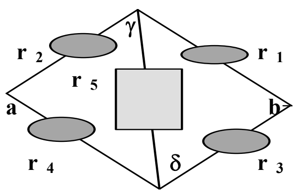


*Figure 1. R_{eff} = R (**a-b**) - resistance of module is measured by use **a** and **b** points. For equilibrium situation electric potential in γ and δ points are equal (balanced points); so R(a-b) becomes independent on the value of resistance $\mathbf{r_5}$. It is valid also if $\mathbf{r_5}$ **=0.** (Electrical Wheatstone bridge).*

Our aims are to represent both the quantitative model of initial stage of materials' fatigue and the new way of fatigue damage analysis of construction materials by using SEs .

The ways of realization. Effective rheological output parameters (J_{eff} and η_{eff} or $\mathbf{Q}^{-1}_{eff}$ - coefficient of nonlinear internal friction) of a real construction beam are also modeled by lattice in the knots of which rheological elements – elasticity (J_k, k = 1,2,…,K_{cm}; K_{cm} – the total number of granules [or clusters] of CM) and /or viscosity (η_k) are randomly located. J_k and η_k – are elasticity and viscosity of CM granules which are randomly connected with neighboring granules [3].

Real CM has an intricate potential relief. So in it there are couples of points (***balanced points***) with identical potential. Their space function of distribution f_n (x, y, z) can be presented by the complete orthonormal series of functions ({ φ_ν , 1 } ; $-\infty < \nu < +\infty$), which obey the baker (**B**) transformation [3,4]. After the loads being imposed some of balanced points migrate in the CM space. Their space function of distribution f_n also obeys baker transformation (See Fig. 3a, 3b, 3c). It gives the possibility to determine common law controlling the migration of defects complex.

Ample grains do not take part in fatigue process of both a polycrystal CM and a SE. Along with growth of the number of strongly deformed grains in polycrystal CM as well as in SE there are also an ample grains possess their original state. The simple model (See Fig.2) describes these situations is given in [3]. There is also next sufficient **conclusion :** *When random deformation process taking place at regular (unit) intervals of time - τ, the CM's and the SE's responses at both a fast ($\tau << \tau_c^{(SE)}$) and a slow*

*($\tau > \tau_c^{(CM)}$) loads can be found by using distribution function $f_n(x, y, z; \tau)$. Their distribution functions $f_n(x, y, z; \tau)$ can be expanded to the series by full orthonormal set of functions $\{\varphi_\nu, 1\}$[3,4] . $\{\varphi_\nu, 1\}$ are eigenfunctions of the operator of "age" is, by definition, a self – adjoint operator **T** [4] : $T\,\varphi_\nu = \nu * \varphi_\nu$, $\nu = 0, \pm 1, \pm 2, \ldots, \pm\infty$. $\{\varphi_\nu, 1\}$ also suit to baker's transformation (**B**). It gives one the opportunity to simulate a fatigue process in both the CMs and SEs. And it is the main reason why for all kinds of imposed deformation (extension-compression; bending variations with different coefficients of asymmetry; various spectra of imposed deformation), at which the output parameters (electric resistance R_n for SE and internal friction Q_n for CM) of materials are recorded in equal time (τ) intervals, the next recurrent relations take place:*

$$R_{n+1}[\sigma] = \mathbf{O}_n * R_n[\sigma] = B_n * R_n + (1-B_n) * M_n \ ; \qquad (1)$$

$$Q^{-1}{}_{n+1}[\sigma] = \mathbf{O}_n * Q^{-1}{}_n[\sigma] = b_n * Q^{-1}{}_n + (1-b_n) * m_n \ . \qquad (1a)$$

Here: R_n is the electric resistance of SE measured under the same state of the environment; n is the ordinal number of measurement (n = 1,2,3, ..., g); g is the maximum number of the measurement performed; $\mathbf{O}_n$ is the loading operator transferring the SE resistance from R_n-th state to R_{n+1} -th state ; σ is a complicated

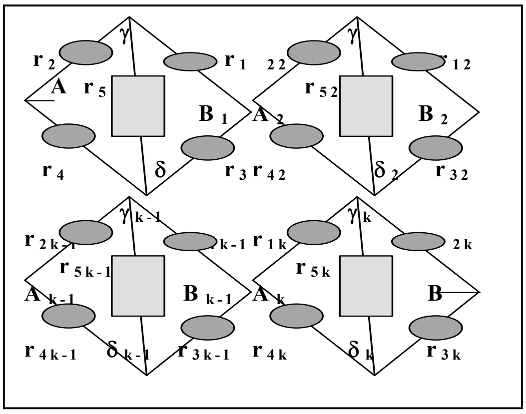
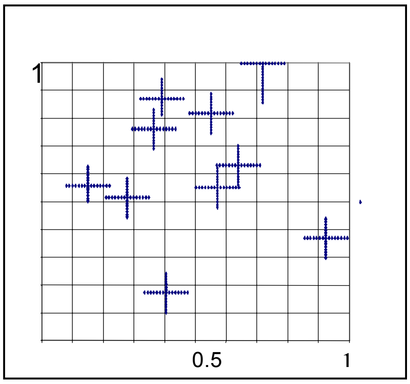


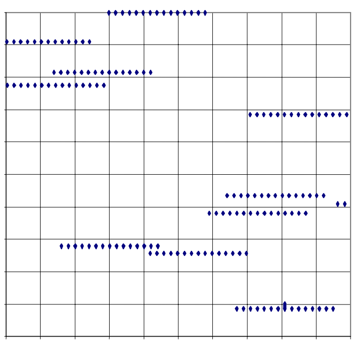
*Fig.2. One port network resistance R_{eff} = R (**A-B**)*
Some of grains do not take part in R_{eff} performance. $\Delta R(\sigma, N) = R_{eff}(\sigma, N) - R_{eff}(\sigma, 0)$;

$$\Delta R(\sigma, N) = \sum_{k=1}^{L} [\, g_k * \Delta R_k(\sigma, N) \,] \ ; \qquad \sum_{k=1}^{L} g_k = 1.$$

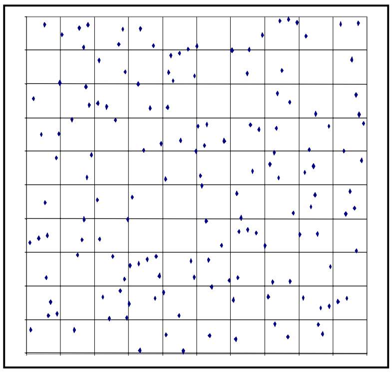
*I) Equilibrium situation - **active module :***
*R (**A-B**$_1$) $\equiv R^*_{20}$;*
*II) Non equilibrium situation –**passive module:***
*R (**A-B**$_1$) $\equiv R^*_{10} > R^*_{20}$*



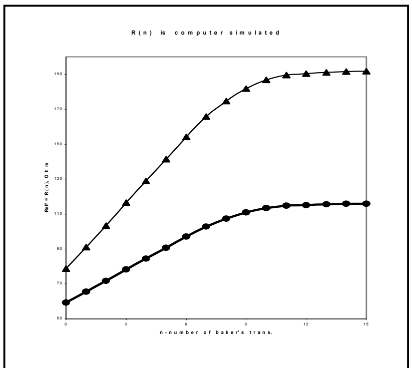
a)



b) ***B***^{1}



c) ***B***^{8}



d)

Fig. 3a. N_e - original equilibrium points are arbitrary located at a SE' space. $N_e = 10$; $N_1 = 15$; $N_2 = 15$; N_1 – compressible subset (contains active module – R^*_{20}); N_2 -expandable subset (contains passive module – R^*_{10})

Fig.3b. SE's state after 1 baker transformation: $N_e = 10$; $N_1 = 15$; $N_2 = 15$;

Fig.3c. SE's state after 8 baker transformations: $N_e = 10$; $N_1 = 15$; $N_2 = 15$;

Fig.3d SE's R_{eff} versus number n discrete deformation process taking place at regular intervals of time - τ . Simple mode of loading. $R_{eff} = R_\nu$ - is computer simulated: 1) $R_{1,0}$ = 120 Ohm ; $R_{2,0}$ = 40 Ohm;
2) $R_{1,0}$ = 200 Ohm ; $R_{2,0}$ = 40 Ohm

parameter to characterize the type of imposed deformation ; the "time series", composed of experimental data of the types:

$$R_1 , R_2 , \dots , R_{n-1} , R_n , R_{n+1} , \dots , R_g ; \qquad (2)$$
$$Q^{-1}_1 , Q^{-1}_2 , \dots , Q^{-1}_{n-1} , Q^{-1}_n , Q^{-1}_{n+1} , \dots , Q^{-1}_g . \qquad (2a)$$

By using the Grassbereger and Procaccia [6] procedure, efficient phase dimensionalities K_g of the time series (2) is calculated. K_g is integer and, in general, depends on the magnitude of the chosen interval (τ).

Taking into account the numerical value of K_g , formulas (1) for R_n, and using formulas of regression, we can find the dependence of parameters B_n and M_n on $n*\tau$ ($n > K_g > 2$).

The relationships

$$B_n = B_{n-1} = B_{n-2} = \dots = B_{n - Kg+1} \; ; \quad \text{and} \quad M_n = M_{n-1} = M_{n-2} = \dots = M_{n-Kg+1} \qquad (3)$$

take place. As a result R_{n+1} can be forecasted from previous values of R_n (2) (See Fig.4, Fig.6).
The same procedure can be used to find b_n , m_n , and to forecast Q^{-1}_{n+1} having time series (2a) (See Fig.8)

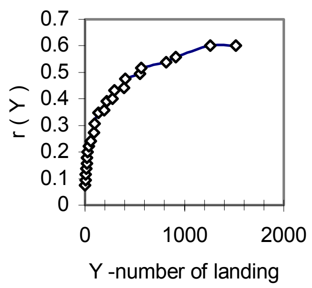


Fig.4 Irreversible random (TU-154B wing spectrum) deformation r-Y. Here Y is number of plane landing; $r (Y) =(R_{Y,eff} – R_{0,eff})/ R_{0,eff}$

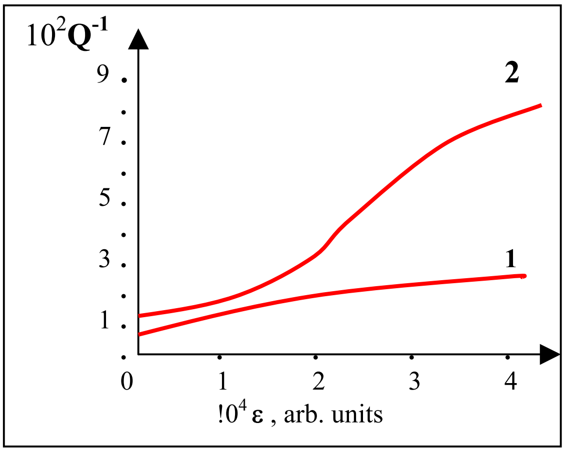


Fig. 5 Internal friction of alloy's sample Q^{-1} versus on imposed deformation ε
1– After imposed 500 cycles of 25 kg/mm^2 load
2 - After imposed 10^4 cycles of 25 kg/mm^2 load

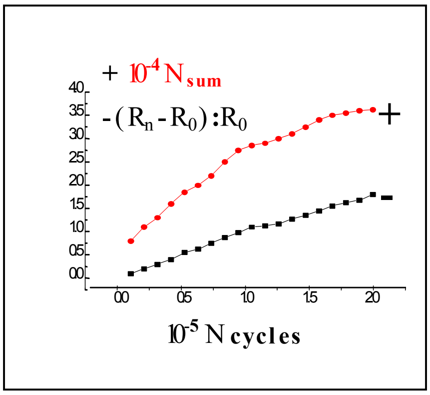


Fig.6 SE resistance [$(R_n - R_o)/ R_o$] and total acoustic emission N_{sum} of the D-16T spesimen versus number of cycles N of the imposed deformation corresponding to a 25 kg/ mm^2 load. The asymmetry coefficient is unity (m =1).

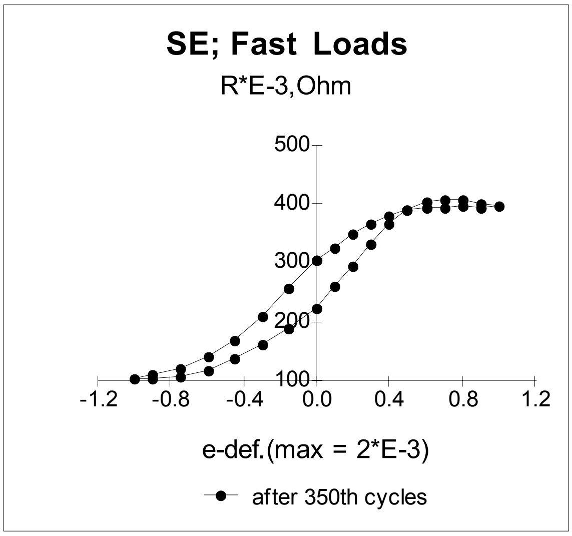


Fig 7. SE's resistance R_{eff} versus on imposed deformation ε, after imposed 350 cycles of fatigue loads, the single fast cycle is imposed. The R_{eff} - ε curve was automatically recorded within this fast cycle.

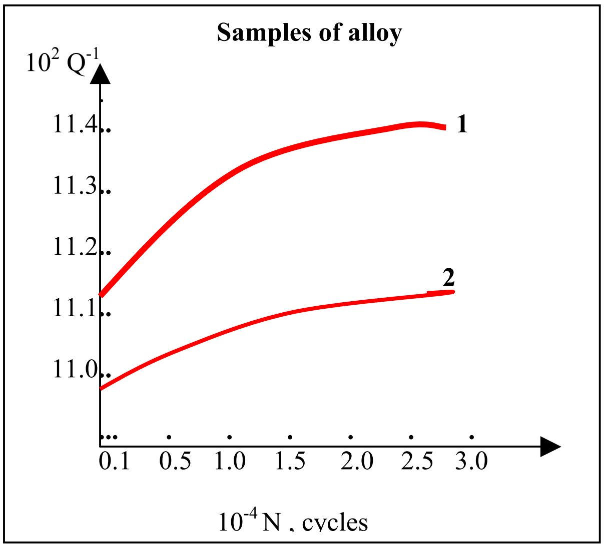


*Fig. 8 Internal friction of alloy's sample **Q^{-1}** versus on number N cycles of the imposed deformation corresponding to both 32 kg/mm^2 **(1)** and 26 kg/ mm^2 **(2)** loads. The asymmetry coefficient is unity (m =1).*

To gain a greater insight into why the R_{eff} - N dependence has the form given in Fig.4,6 assume that for every module (Fig.1)

$$\Delta R_k(\sigma, N) = \begin{cases} G(\sigma, m)*N & \text{if } N \le N_k \\ G(\sigma, m)*N_k & \text{if } N \ge N_k \end{cases} \qquad (4)$$

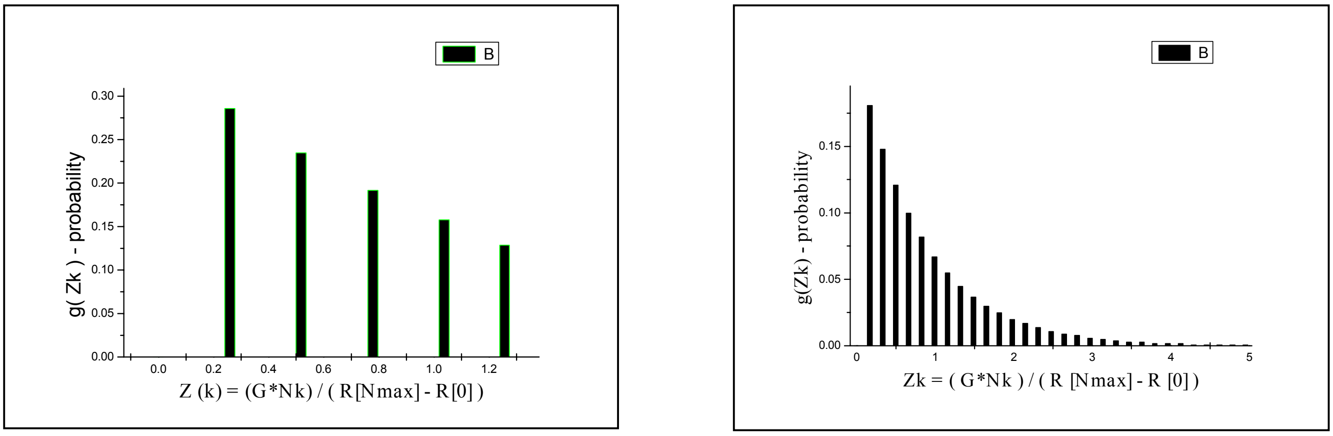
takes place; N_k varies in value. A scale factor - $G(\sigma,m)$ is the same for each module of the SE and depend on the amplitude - σ and degree of asymmetry - m of the imposed regular cyclic deformation.

Each module (Fig.2) will be able to contribute to the ΔR_{eff} in accordance with statistic g_k [7]:

$$\Delta R(\sigma, N) = \sum_{k=1}^{L} [\, g_k * \Delta R_k(\sigma, N) \,] ; \qquad \sum_{k=1}^{L} g_k = 1. \qquad (5)$$

$\Delta R_k(\sigma,m; N)$ - variation of resistance of a k-th module depend on the amplitude - σ and degree of asymmetry - m of the superimposed regular cyclic deformation. N is the number of cycles. For the sake of convenience, assume that $\Delta R_{max} = M_g(\sigma, m)$ and

$$Z_k = G(\sigma,m)*N_k / M_g(\sigma,m) \quad , (k = 1,2,3,..., L). \qquad (6)$$



a) b)

Fig. 9 . The state of SM-film after be loaded : a) 250 and b) 1000 cycles of regular deformation :
*(σ_{eff} = **17 Kg/mm^2**); σ_a = 7.42 Kg/mm^2 ; σ_m = 12.04 Kg/mm^2*

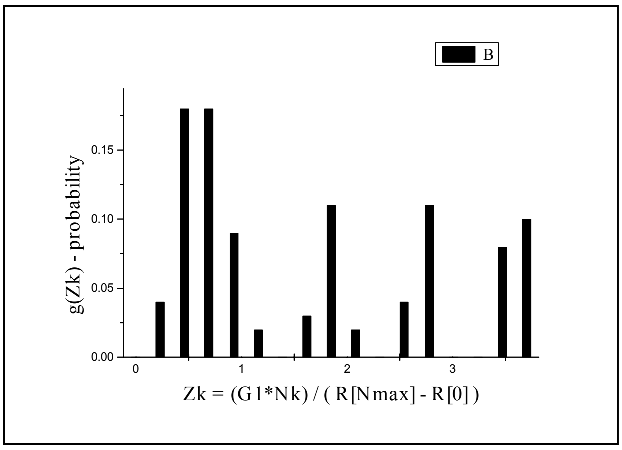


*Fig.10. The state of SM-film after be loaded 800 cycles of arbitrary deformation (σ_{eff} = **20.02 Kg/mm^2**)*

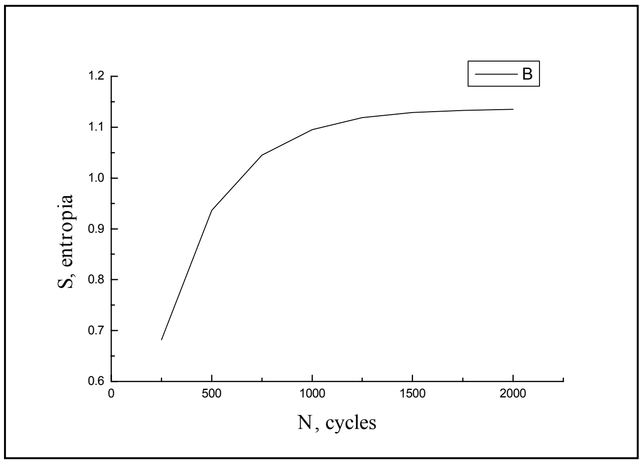


*Fig.11 . The increase of entropy (**S**) versus (**N**) regular cycles.*

Z_k and g_k can be found from experimental data, Fig.4 (or Fig.6, or Fig 8). Proceed as follows:

$$\Delta R(N) = G*N* \sum_{k=1}^{L} g_k = G*N, \qquad 0 \le N \le N_1$$

$$\Delta R(N) = G*N_1*g_1 + G*N*\{1-g_1\} \qquad N_1 \le N \le N_2$$

$\Delta R(N) = G*N_1*g_1 + G*N_2*g_2 + G*N*\{1-g_1-g_2\}; \qquad N_2 \le N \le N_3$

$$\ldots\ldots \qquad (7)$$

$$\Delta R(N) = G*\sum_{k=1}^{L} [N_k*g_k] \qquad N_L \le N$$

Notice that $N_1 < N_2 < N_3 <.....< N_L$ and N vary in each of interval of $[N_k, N_{k+1}]$. Let us take a derivative of ΔR (N) with respect to N in each of (7) equalities. Then each subsequent equality can be subtracted from the preceding one. As a result one find all quantities of g_k, N_k, as well as $G(\sigma,m)$ and $M_g(\sigma.m)$. Figure 9 (a,b) and Fig.10 present the states of SE - film after both various number of cycles and value of the imposed deformation. Information entropy S

$$S = \sum_{\hat{e}=1}^{L} [g_k*Ln\, g_k]. \qquad (8)$$

is a measure of the amount of disorder (different states) in SE states.
The way mentioned above can also be used to find from experimental data (as Fig. 8) the features of the CMs, possess both the various types of grains and the various types of local structures which readily rearranged to each other at the local zones.

This model admits control of the structure mutations in both a CM and a SE after N cycles of imposed regular deformation. Fig. 9a – 9b show the regular decrease of probability g_k for modules having a big value Z_k (see (6)). For non-regular deformation there is other situation (see Fig.10). The increase of entropy S (see (8)) of SE is presented on Fig.11.

Conclusion. The various impurities in Aluminum implement the various resistance to fatigue of an Aluminum alloys' samples. The same situation one has in heterogeneous materials, that are used to form the sensitive elements (SEs) for fatigue gages [1,2]. The SEs are rigidly installed on the Aluminum alloys' samples and the same spectrum of deformation imposed on both of them. We have educed that the fatigue features of a SEs, which have a various impurities, can be reflected on each other [1].

After imposing a limit number of cycles of fatigue deformation, that change both the CM's structure and the SE's structure, the single fast cycle of deformation with selected value of amplitude is imposed on the sample. The R - ε (R – electrical resistance of SE and ε - value of imposed deformation) curve, that was automatically recorded within this fast cycle of deformation, permits one to bring out the forthcoming structures of SE and its features, that will take place at the near future cycles of imposed deformation. Reiteration of these processes also for Q^{-1} - ε curves gives the chance to do the monitoring of fatigue features of polycrystal alloys' samples .

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