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SIMULATION OF CRACK GROWTH LIFE IN THE SKIN ELEMENTS OF AVIATION CONSTRUCTIONS UNDER VARIABLE-AMPLITUDE LOADING[1]

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The paper shows possibility to use Paris-Erdogan equation for simulation of fatigue crack growth under random loading. In the considered equation effective stress intensity factor range was introduced. The introduced methodology for crack growth simulation is based on the concept of a “basic” random loading. The discussed methodology included consideration of overloads influence on the fatigue crack growth. The theoretical models are based on the experimental researches of fatigue crack growth under random loading that have realized during specimens fatigue tests of two Al-based alloys (D16AT - the same as 2024-T3, and B95ATB – 7075-T6). In all cases the random loading has been considered as Gaussian processes of cyclic loading with introduced and discussed parameters of the investigated processes.

Keywords: random cyclic loads, overloads, peak factor, fatigue crack growth, simulation, variable-amplitude loading.

INTRODUCTION

Fatigue crack growth under random cyclic loadings has been considered in a different manner using two principal ideas. The first is based on reorganization of random loads sequences in the sequence of deterministic blocks. A block of cyclic loading was created using two-parametrical schematization of cyclic loads sequence by a well-known method named “rain-flow”. Then different types of models for crack growth simulation were used and, as a rule, tests results were used for experimental verifications of introduced models [1]. The second idea is based on the Paris-Erdogan-Equation (PEE) with parameters defined for materials under regular cyclic loads. The random character of cyclic loading was considered by using some equivalent of stress intensity factor range $\Delta K_{eq.}$ The ΔK_{eq} - factor is calculating by statistical characteristics of cyclic loading processes.

The ΔK_{eq} – factor can be determined by using constant of stress range $\Delta\sigma_{eq}$ [2; 4], independent random value [5], or – as stochastic function [6].

The paper was to answer three questions. The first – can PEE be used for simulation of materials fatigue cracking under random loading, and what is the area for PEE application. The second –how can ΔK_{eq} – factor be calculated in the case of Gaussian processes of cyclic loading. The third - what is the accuracy of crack growth rate simulation for materials under random cyclic loads.

TESTING UNDER RANDOM LOADING

Material and Specimen

The investigated materials for experimental research were used in aircraft IL-86 wing. The principal structures the aircraft wing, their thickness and type of materials are shown in table 1.

Table 1

Materials used in principal elements of the wing design of aircraft IL-86

Type of wing principal elements	Structural materials	Thickness of structural elements, mm
The top panel covered	V95T, V95T2	3…10
The bottom panel covered	D16T, D16AT	3…8
Fittings	D16	2…7
Spars	D16T, V95	5…20
Stringers	D16	2…7

[1] *This article was based on the authors report of the 18-th European conference on Fracture / Dresden, Germany.*

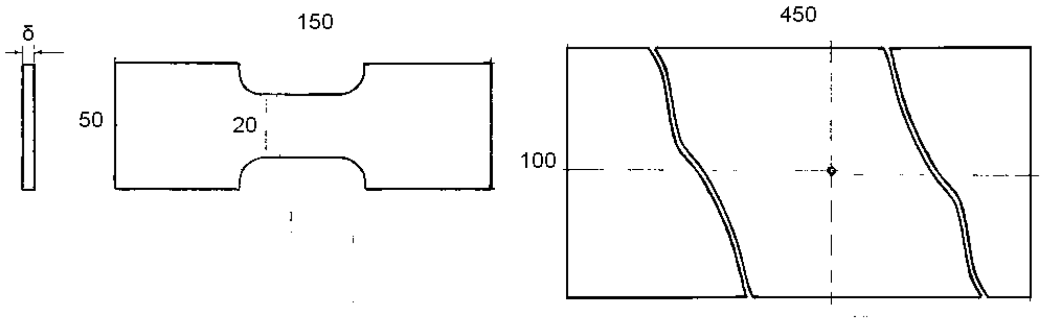
Preliminary tests were conducted of specimens under tension of Al-based alloys D16ATcl and V95ATV for estimation of their mechanical properties. Specimens shape and sizes are shown in Fig.1a. Tests were performed on the electro-hydraulic MTS test-machine with automatical system of the deformation diagram recording. The average values of mechanical properties were received after of processing 30 diagrams (for 10 specimens of each type of alloys), table 2.

Table 2

Mechanical characteristics of investigated materials

Alloy	Specimens thickness, mm	Yung Modulus, MPa	Yield Stress, MPa	Ultimate stress, MPa
D16ATcl	8	69820	336	452
D16ATcl	3	73360	333	474
V95ATV	3	70480	412	516

Fatigue crack growth rate under random cyclic loads has been investigated on the specimens of the same materials which had shape as a plane with thicknesses 3 and 8 mm of 450x100 mm in length and width respectively, Fig. 1b. The specimens were made from one sheet along the direction of plastic deformation during manufacturing procedure that is realize in practice for aircraft components.



a b

Fig. 1. Overview of specimens used for: a - tension; b - cyclic tests. The stress concentration had the central hole of 1.5 mm in diameter with two symmetrical cuts with planes having orientation perpendicular to the axial of cyclic loading

Test procedure under spectrum loading

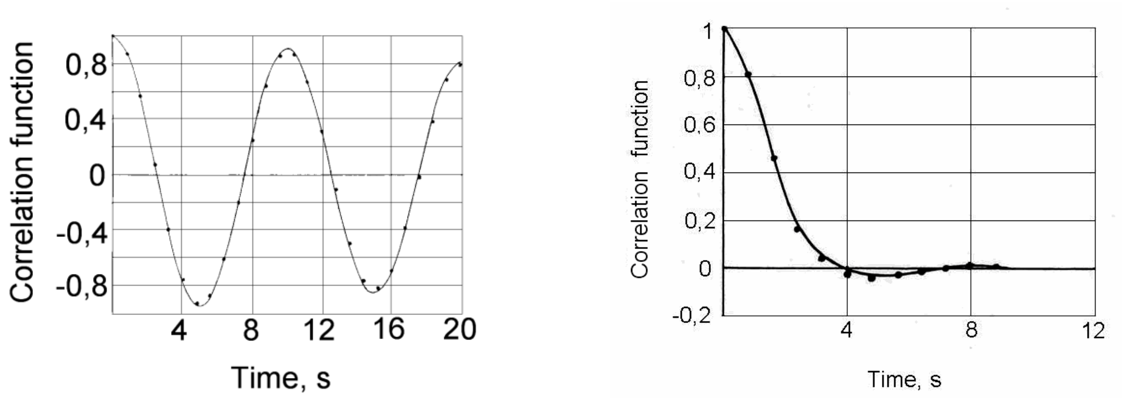
Fatigue test was conducted in two stages. First, the crack was initiated in specimens from the notch under regular cyclic loading with maximum stress level 70 MPa at frequency of 10 Hz. The crack has been extended up to 6 mm.

Then different types of cyclic loads sequences for specimens with preliminary cracks for their tests under random loading were introduced. The test procedure has provided identical conditions for all specimens before testing under random loading.

All types of random cyclic loads sequences were reproduced in the manner of Gaussian-processes with correlation function

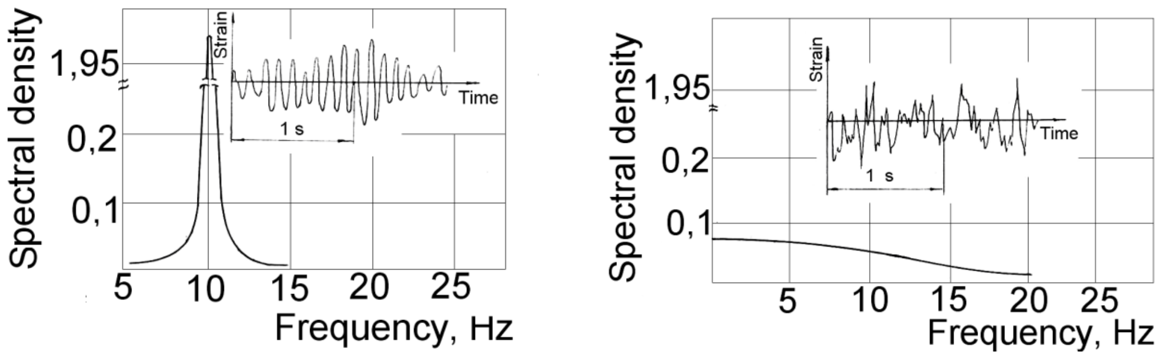
$$R(t) = \exp(-\alpha\,|\,t\,|)\left[\cos\omega_0 t + (a/\omega_0)\sin\omega_0\,|\,t\,|\right]. \tag{1}$$

In Eq. (1) ω_0 is the frequency of processes. It was constant, ω_0 = 62.8 s^{-1} for all investigated processes. The α-parameter characterizes difference between narrowband and broadband of random processes. The complexity of investigated Gaussian-processes is characterized by æ-factor. Its value characterizes ratio between the number of processes crossing average positive value and number of maximum values of stresses for the process.



a b

Fig. 2. Correlation functions of two Gaussian processes. The lines describe theoretical estimations. Points show experimental data: a - correlation function of narrowband process α = 1s^{-1}, æ = 0,94; b - correlation function of broadband process α = 75 s^{-1}, æ = 0,52

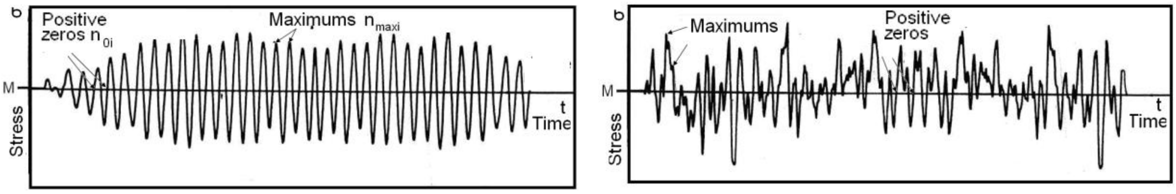


a b

Fig. 3. Spectral densities of two Gauss processes: a - spectral density of narrowband process α = 1s^{-1}, æ = 0,94; b - spectral density of broadband process α = 75 s^{-1}, æ = 0.52

Details of tests procedure for simulation a sequence of cyclic loads by different programs, the description of algorithm and methods of cyclic loads level accuracy estimation is described in paper [7]. All specimens were tested in the range of α-parameters (1 – 75) s^{-1}. Gaussian-processes had clear difference in their complexity that can be seen from the Figs. 2 and 3. The correlation functions and spectral densities for two compared processes have principal difference. That is why the considered number of Gaussian-processes allowed generalizing of the investigation results for many situations that can be seen in practice for aircraft structures.

Registration of realized Gaussian-processes took place on the special tape-recorder in two directions. Examples of narrowband and broadband of reproduced processes are shown in Fig.4a, b. Evidently that the cycles of a narrowband process are very clear and have approximately the same frequency. Amplitudes have good correlation and the process can be easily schematized. Consideration of different Gaussian-processes has demonstrated a big influence on the crack growth rate, the standard deviation “S” and average value of cyclic loads “M” of investigated processes. That is why in conducted fatigue tests both parameters were the same and their values were S=30 MPa and M=70 MPa.

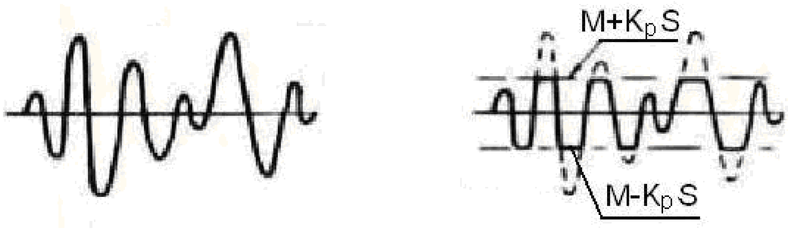


a - narrowband process (α = 1, æ = 0,94) b - broadband process (α = 75, æ = 0,52)

Fig. 4. Two fragments for different (a), (b) random cyclic loads sequences with different values of α-parameter and æ-factor of irregularity. M – average value of spectrum loads

During amount number of cyclic loads there can be seen high level of cyclic stress σ_i, which cannot be reproduced by the used test-machine. That is why it was used for random cyclic loads for maximum and minimum stress levels. However, tests results specimens under loads with constant amplitude with single overloads have shown that the introduction borders for stress level in random processes will have influence on the crack growth rates.

For describing the influence of overloads K_p-factor is introduced. Which is the factor characterizing the range of stress inside the introduced borders. The process will be named "bordered" with K_p-factor, if the introduced borders are characterized by ratio M± K_pS, Fig. 5.



a b

Fig. 5. Illustration for the introduced knowledge about cutting operation:
a - initial process; b - cut process

FATIGUE TESTS RESULTS

Fig. 6 shows the assembly of kinetic curves for fatigued specimens of D16ATcl aluminum alloy. There is also shown several positions for borders of the transformed process with different values of K_p-factor. It is clear that for different values of K_p-factor but for the same Gaussian-process there is no difference in statistical characteristics of the investigated random loads sequence. The correlation functions, æ-factor and α-parameter were the same. That is why for statistical analyses the different processes with different values of K_p-factor have no difference.

From the Fig. 6 follows that extremely values of stress have appeared at the moments of t_1 and t_2 directed to significant decreasing of crack growth rate in the tested specimen under random cyclic loading with Kp =5. Introduction of "cutting operation" with different values of K_p-factor has dramatic influence on the discussed kinetic process or crack growth rate. Lower value of K_p-factor has more intensive influence on the crack growth rate than higher value of K_p-factor if it is compared with the main process before the "cutting" operation. For example, kinetic curves in the cases of Kp=2 and K_p =2,5 have no change in shapes but the curves in the other cases have shapes variations due to maximum of cyclic loads because of overload influence on the crack growth rate. That is why for the cases of Kp=2 and K_p =2,5 applicably to the same random process crack growth period is minimum.

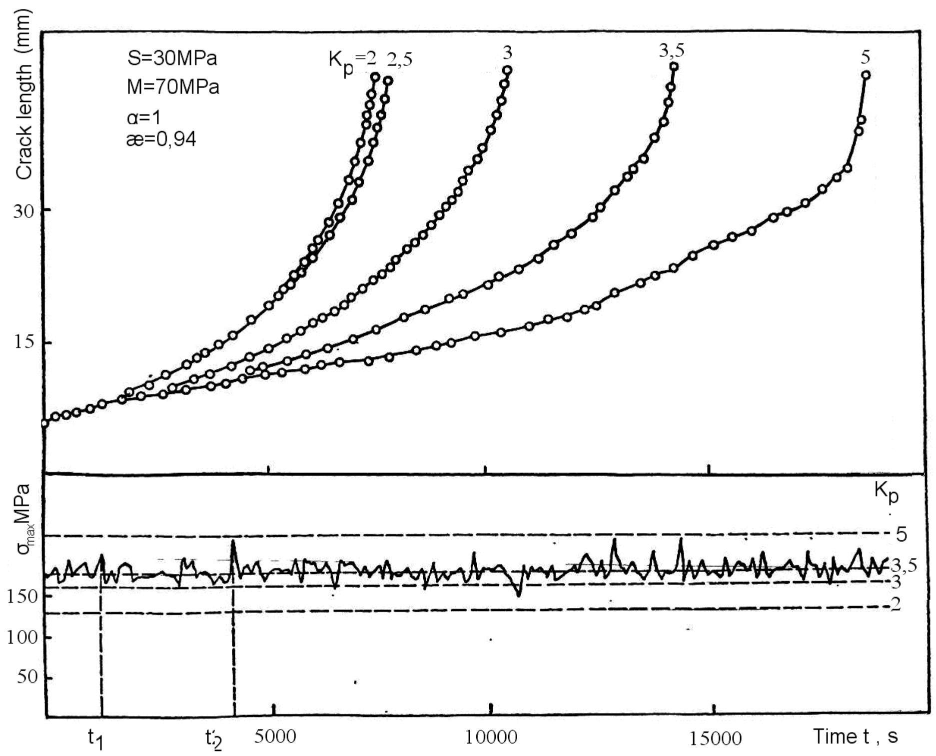


Fig. 6. The fatigue cracks growth curves in specimens under the same random loading processes with different values of K_p-factor

Consequently, crack growth period is determined, on the one hand, by the integral parameters of Gaussian-process spectral density, which have sense of introduced energy in metals at unit time, but, on the other hand, there are extremel values of stress distribution and material elastic-plastic characteristics that influenced the crack growth rate. The energy distribution by the different frequencies of Gaussian-processes which were described by the value of æ-factor is the characteristic of the crack growth of the second term that can be seen from the result of fatigue tests with different values of æ-factor [7].

K_p-factor decreasing directed to border large of dispersion for of normalized maximum stresses in Gaussian-process, Fig. 7. In the case of narrowband Gaussian-process density distribution of normalized maximum stresses can be approximated density of Relay-distribution (see curve number 1 in Fig. 7).

Fig. 7 shows that the "cutting operation" directed to sequentially excluding rear maximum values of stresses which can perform ahead of a crack tip areas with high level of residual stresses due to material plastic deformation under overload which influenced crack growth retardation for the next time of cyclic loading. It can also explain crack growth period decreasing for K_p-factor decreasing (see Fig. 6). The discussed result can be seen from the other experiments [8]. It was investigated influence of stress high levels on the regularities of the fatigue crack growth in the case of specimens of 2024-T3 and 7075-T6 Al-based alloys subjected to typical programs of cyclic loading named TWIST and FALSTAFF.

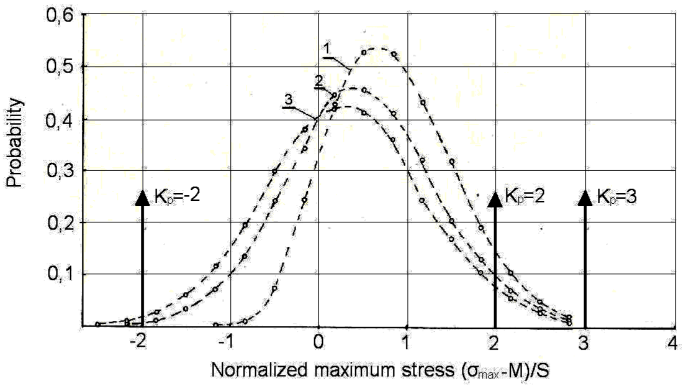


Fig. 7. The density distribution of normalized maximum stresses of Gaussian-processes with different values of K_p - factor 1 - æ = 0,94; 2 - æ = 0,66; 3 - æ = 0,52

DISCUSSION

The processes with K_p=2 such as "basic" random loading of Gaussian-process will be considered. In the considered case the crack growth rate is maximum but crack growth period is minimum [7; 9; 10]. If this type of "cutting" procedure is used for simulation of the fatigue crack growth rates results of crack growth period the estimation will have safety-factor. It is in a good correlation with orders to aircraft structures for civil aviation. That is why specimen tests for estimation crack growth period in aircraft structures can be recommended to realize with "cutting" procedure by using rule of $M \pm K_pS$. This rule for fatigue tests allowed to present experimental results in the manner of well-known kinetic curves with linier parts because the effects of local crack growth variations are minimum.

In the discussed results of investigation crack growth simulation for random cyclic loading was considered based on the idea about "basic" random loading of Gaussian-process. Because minimum loading interaction effect can be seen for "basic" random loading the first stage of crack growth simulation has to be realized in the "basic" case. Different linear models for the material cracking simulation can be used in this case. The second stage of the material fatigue cracking simulation can be realized by using non-linear models because maximum values of stresses can be considered step-by-step.

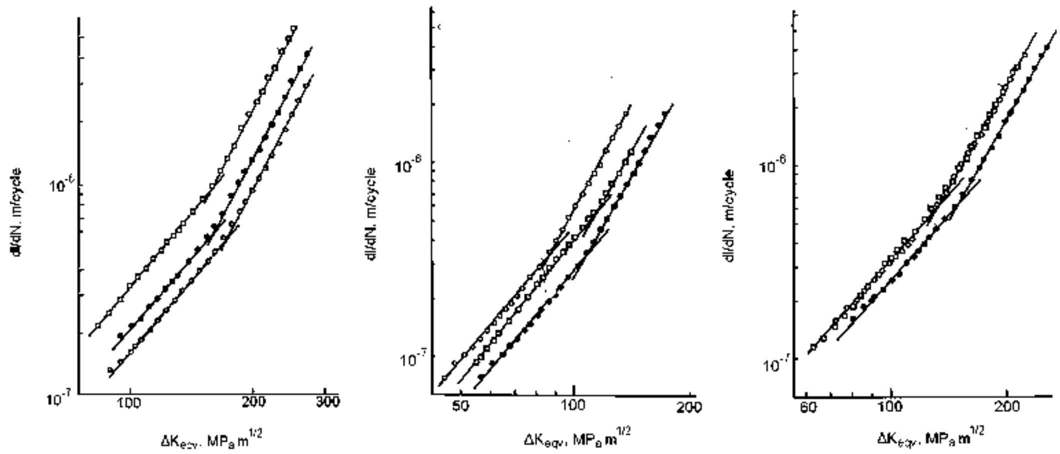
The present paper discussed PEE using for simulation of fatigue crack growth applicably to Gaussian-processes of cyclic loading when equivalent value of stress intensity factor range ΔK_{eq} is calculated by the statistic characteristics of random cyclic loads:

$$dl/dN = C\Delta K_{eq}^{m} \quad ; \quad \Delta K_{eq} = \Delta\sigma_{eq}\sqrt{\pi l/2}F \ . \qquad (2)$$

In Eq.(2): *C* and *m* are parameters of PEE; *F* is functional correction for geometry of structural elements specimen; *l* is crack growth length; $\Delta\sigma_{экв}$ is equivalent of stress range.

The value of $\Delta\sigma_{экв}$ was calculated by relations using: 1) value of process standard deviation - $\Delta\sigma_{eq} = 2\sqrt{2}S$; 2) value of average stresses range of Gaussian-process - $\Delta\sigma_{экв} = \Delta\overline{\sigma}_{cx}$; 3) value of mean-square stresses ranges deviation $\Delta\sigma_{eq} = \sqrt{\Delta\overline{\sigma}_c^2}$. The stress range of $\Delta\sigma_{cx}$ has been discovered from the cyclic loads sequences schematization by the "rain flow" method.

Fig. 8 shows the kinetic curves for tested specimens of 3 mm in thickness of D16ATcl aluminum alloy under the "basic" condition and under the regular cyclic loads. The curves for different values of $\Delta\sigma_{eq} = 2\sqrt{2}S$ (see Fig. 8a) were constructed for a number of cycles that have been considered for a number crossing the line which indicated "M", for example, on Fig. 4. Curves for different values of $\Delta\sigma_{eq} = \Delta\overline{\sigma}_c$ and $\Delta\sigma_{eq} = \sqrt{\Delta\overline{\sigma}_c^2}$ were considered for a number of cycles that have been discovered as a result of cyclic loads sequence schematization by the "rain flow" method.



a
- ● narrowband proc;
- ○ broadband proc;
- □ constant amplitude

$\Delta\sigma_{eq} = 2\sqrt{2}S$

b
- ●○ broadband proc;
- □ constant amplitude;
- ● $\Delta\sigma_{eq} = \sqrt{\Delta\overline{\sigma}_c^2}$;
- ○ $\Delta\sigma_{eq} = \Delta\overline{\sigma}_c$

c
- ●○ narrowband proc;
- □ constant amplitude
- ● $\Delta\sigma_{eq} = \sqrt{\Delta\overline{\sigma}_c^2}$
- ○ $\Delta\sigma_{eq} = \Delta\overline{\sigma}_c$

Fig. 8. Fatigue crack grows under random loading and regular loading (constant amplitude)

To be clear of the effect which has been seen for the kinetic curves because of the evidence of two stages of crack growth, the macro-fracture surface analyses have been used. It was discovered that the dramatic change of the crack growth kinetics takes place because of transition from the flat fracture surface which has orientation near perpendicular to the specimen loading direction, to the area of shear lip formation which reflects plain-stress condition for material stress-state.

The kinetic curves for regular cyclic loading have been constructed for fatigue tests of specimen under stress amplitude of σ_a= 40 MPa $\approx\sqrt{2}S$. In the case Gaussian process for broadband the regular cyclic loading was considered with value of σ_a= 20 MPa$\approx\sqrt{\Delta\overline{\sigma}_c^2}$, and for narrowband it was considered with value of σ_a= 30 MPa$\approx\Delta\overline{\sigma}_c$.

Comparing the test results for random and regular cyclic loading have shown that the introduced method is realistic in estimation of fatigue crack growth rates which values have maximum from the all possible estimations of intensiveness of material fatigue cracking. Material fatigue cracking has 1,2-2,0 times intensiveness in the case of regular cyclic loading with $\sigma_a \approx\sqrt{2}S$ than in the narrowband case, and 1,7-2 times intensiveness than in the case of broadband of Gaussian-process.

CONCLUSION

The method of kinetic construction in the case of random loading with introducing “cutting” procedure to exclude irregularities of discovered kinetic curves was introduced. Reorganizing random cyclic loads sequences using the relation M±2S was suggested. This case of cyclic loading has to be considered as “basic” condition of cyclic loading. The “basic” condition is minimum for fatigue crack growth period.

The Paris-Erdogan-Equation can be used for simulation crack growth rates based on the equivalent value of stress intensity factor range $\Delta K_{eq} = \Delta\sigma_{eq}\sqrt{\pi l/2}F$. In the case of th stress range calculation by the ratio $\Delta\sigma_{eq} = 2\sqrt{2}S$ the result of fatigue crack growth simulation has higher values for narrowband and broadband processes. Damages accumulation in the investigated materials takes place for this case with intensiveness 1,2…2 times that in the case of narrowband case.

The better case for fatigue crack growth simulation by the Paris-Erdogan-Equation have been discovered for narrowband of Gaussian-processes with accuracy for crack growth period approximately 5…10% for tested specimens when values of equivalent stress intensity factor range was calculated with $\Delta\sigma_{эq} = \Delta\bar{\sigma}_c$.

Performed investigations, test results and crack growth simulations have shown that for the narrowband of Gaussian-processes values of equivalent stress intensity factor range ΔK_{eq} better described ratio $\Delta\sigma_{eq} = \Delta\bar{\sigma}_c$ for crack growth rate estimation under random cyclic loading. In the case of broadband Gaussian processes, ratio $\Delta\sigma_{eq} = \sqrt{\Delta\bar{\sigma}_c^2}$ allowed to estimate maximum values of crack growth rates by the Paris-Erdogan-Equation but ratio $\Delta\sigma_{eq} = \Delta\bar{\sigma}_c$ allowed estimating minimum values of growth rates.

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МОДЕЛИРОВАНИЕ РОСТА ТРЕЩИН В ЭЛЕМЕНТАХ АВИАКОНСТРУКЦИЙ ПРИ СЛУЧАЙНЫХ РЕЖИМАХ НАГРУЖЕНИЯ

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В статье приводится обоснование возможности и области применения уравнения Пэриса-Эрдогана для моделирования развития трещин усталости при случайных процессах нагружения. Приводится методика расчетов, основанная на использовании понятия «базового» случайного процесса и введении эквивалентного коэффициента интенсивности напряжений. Исследуется степень влияния перегрузок на скорость развития трещин. Теоретические положения сопоставляются с результатами экспериментальных исследований трещиностойкости плоских образцов-пластин из сплавов Д16АТ (аналог 2024-Т3) и В95АТВ (аналог 7075-Т6). Нагружение в эксперименте представляло собой стационарные гауссовские процессы.

Ключевые слова: случайное циклическое нагружение, пик-фактор, развитие трещин усталости, моделирование, нагрузки с переменной амплитудой.

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