Synergetic Discretely-Likelihood Fatigue Model Based Structure Lifetime Prediction Methods Improvement

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Abstract. This article deals with the problem of residual life estimation. Fatigue test results of different metals and alloys under variable amplitude with two blocks cycles are represented. The results are showing that there are no any dependence with significant coefficient of determination between prior cyclic loading and residual durability. It is shown that test results can be represented in the form of a prior cyclic loading – residual durability correlation field with high dispersion that could be explained by high and low frequency process. This effect is considered within the bounds of synergetic discretely-likelihood fatigue model. According to correlation field structure feature it was offered to use for residual durability calculation the points of correlation field envelope low part as fiducial line.

Introduction

Any aircraft structure designing demands of two conflicting objectives solution: cost efficiency and operational safety providing. Cost efficiency is formed by aircraft lifetime and fuel consumption efficiency that depends essentially on structure weight. Structural safety based on static and fatigue strength that characterized aircraft structure lifetime. That’s why lifetime estimation is most important problem for aviation industry.

Basic lifetime estimation methods can be divided on three groups:

- Calculated methods, which provide lifetime estimation with structure elements durability under constant amplitude loading data using and a cumulative damage theory applying;
- Experimental methods, which provide carrying out fatigue test with service load spectra applying;
- Experiment-calculated methods, which consist in fatigue tests carrying out of structure or its elements, the operating time of which is near or beyond their original design service goal.

Consequently, there are two aims of this methods applying in aviation industry:

1. Lifetime estimation for new aircraft model. Service life calculations are based on fatigue damage models that are used complicated linear and non-linear cumulative fatigue damage theories. All this theories are based on the same idea of fatigue strength fade away with operating time.

Other method is coupon, component and full-scale fatigue testing. Main disadvantage of this method is test duration.

2. Residual life analysis of operating aircraft. In this case teardown aircraft component or coupon from structure elements are fatigue tested in laboratory for residual life equivalent for this aircraft model estimation.

All fatigue tests showed large data scattering for experimental data that make unreliable calculation for structure lifetime estimation. That's why the aircraft structure fatigue strength should be "protected" by safety factor and it leads to the structure weight increasing.

In the early 1970s in National Aviation University were carried out large in statistical aspects fatigue tests for residual durability data scattering cause identification. Observed fatigue test results allow to modify residual durability and lifetime estimation approaches.
First results and their analyze were published in 1982 [1,2].

Research results
In the course of fatigue tests was found the aluminum alloy physical-mechanical properties oscillation. Specimens were tested according to well known method of loading at two stress amplitudes. For first type of researches were used method by means of which a specimen firstly was fatigue tested under one stress level σ_1 for n_1 cycles and then under second stress level σ_2 it was loaded up to fracture (n_2) (Fig. 1).

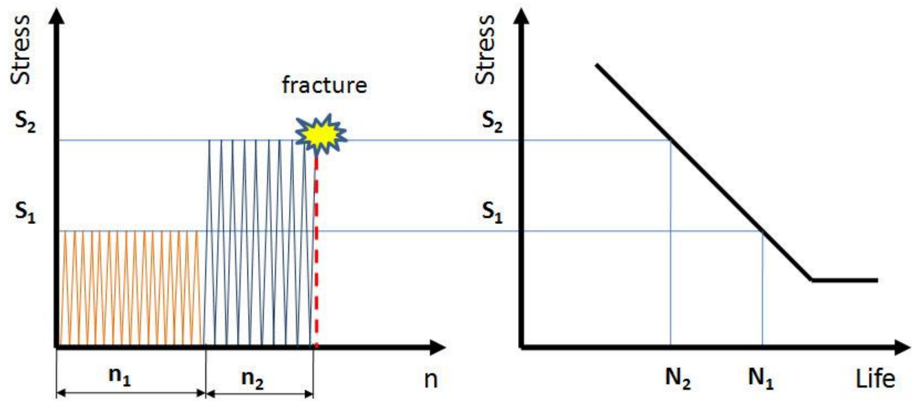


Fig.1 Fatigue test load history and S-N curve

For next fatigue test smooth specimens were used and after n_1 with stress level σ_1 the stress concentrator in form of hole was drilled. The boreholes change distribution of normal stress in specimen reference section and as a result the local normal stress was increased on the concentrator edge. By means of this operation fracture zone was localized.
Special attention was paid to loading amplitude stability and material properties assurance. For this purposes the specimens were manufactured from the same sheet of metal and hole concentrators were drilled by one operator and the same instruments. Fatigue test machine loading regime was the same and was controlled periodically. Cycling loading was performed as cantilever bending with constant amplitude and 25 Hz frequency. These arrangements directed on spread of fatigue test results decreasing. The specimen draw is represented on Fig. 2.

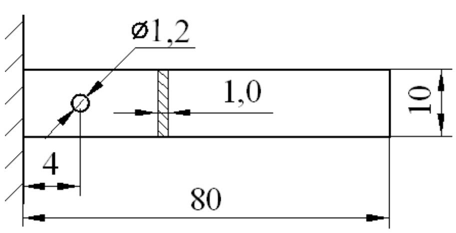


Fig. 2. Specimen draw

There were tested different metals and alloys like aluminum alloy D16T and D16AT (with alclad), 2024-T3, technical pure copper, steels 08kp and 12H18N10T and so one [1,2]. Semilog diagrams represents test results of material on Fig.3. and Fig. 4.
Note next results features:
- extremely low coefficient of determination R^2 for n_2-n_1 results linear dependence, that indicate an impossibility for Miner's Rule applying. For next explanation of n_2-n_1 diagrams we will use "*correlation field*" term instead of "dependence";
- residual durability n_2 sharp increasing appearance (for example, on Fig. 3 for n_1 equal $1\cdot10^3$; $4\cdot10^3$ cycles and so on), that are connected with metal hardening;

- residual durability n_2 sharp decreasing (for example, on Fig. 3 for n_1 equal $0{,}8\cdot10^3$; $3{,}8\cdot10^3$ cycles and so on).

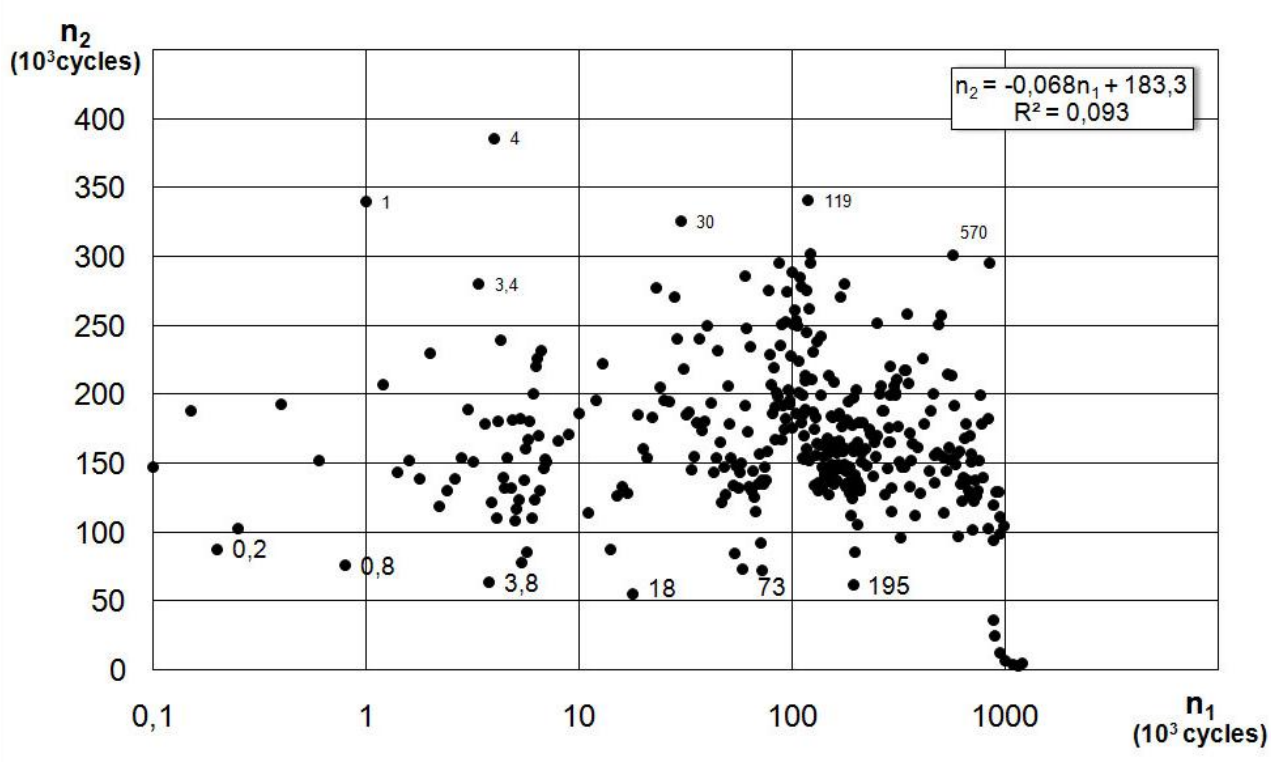


Fig. 3. n_1 vs. n_2 correlation field for copper

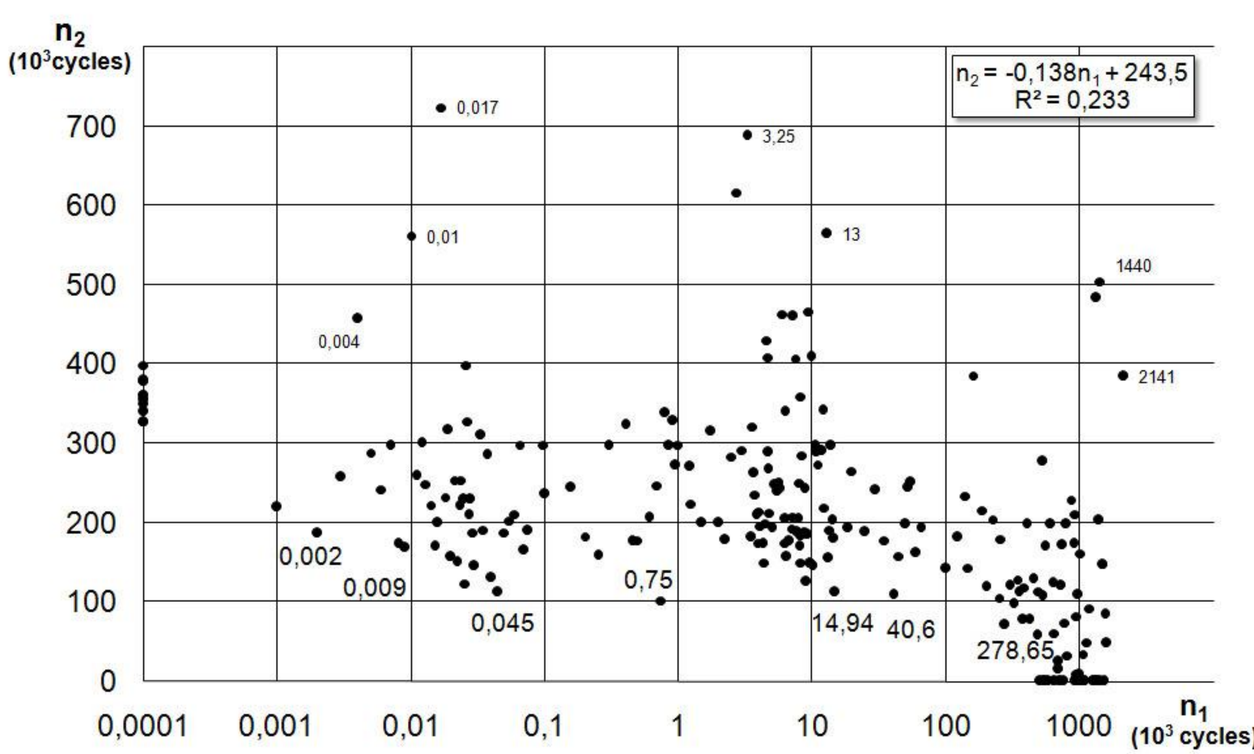


Fig. 4. n_1 vs. n_2 correlation field for steel 12H18N10T

Data analyze allowed to find, that under certain n_1 cycles rapid residual durability n_2 changes occurred. This points are fatigue process bifurcation points. Results of this testing in extensive statistical aspects (more than 250 specimens for each material) fully corroborated residual durability spikes presence.

Appearance of bifurcation points is described by V.Ivanova recurrent relationship [3]:

$$n_1(i) \big/ n_1(i+1) = \Delta^{1/2^{i-1}} \quad , \tag{1}$$

where n_1 – number of cycling loads, that determined bifurcation points appearing;
i – sequence number of bifurcation points;
Δ – metal fracture universal constant, that can be calculated as

$$\Delta = \frac{L}{H_0} \cdot \frac{G}{E}, \tag{2}$$

L – Latent heat of fusion;
H_0 – change in enthalpy under heating from 0 degrees K to fusion temperature;
E и G – modulus of elasticity and shear modulus with 0 degrees K.
For aluminum metal fracture universal constant **Δ** = 0,225, for iron – 0,108, for cooper – 0,168.
Initial fatigue test results analysis shows that V.Ivanova's law could be disseminated on phenomena of the incubation period before crack initiation.
This allowed to define *synergetic discretely-likelihood metal fatigue fracture model* by means of which it became possible to describe the correlation field of test results.
At the present time findings allow to explain prior cyclic loading – residual durability correlation field features.
The main ideas of developed model are:
- prior cyclic loading – residual durability correlation field has irregular shape that is caused by residual durability n_2 sharp increasing (spikes) presence. Spikes constellation is chracterized by spikes series cascade. Each series is formed according V.Ivanova recurrent relationship.

Number of cycles up to first spike for every r-series is called *Basic Bifurcation point* (NBB_r). The value of NBB_r depends on specimen material, thermomechanical treatment, mode of deformation, levels of cycling loads, design and manufacture factors, environmental and so on. Next spikes position in the series is described by Eq. 1.
For example, aluminum alloy (Δ = 0,225) series with NBB=100 cycle is represented on Fig. 5. According to Eq.1. spike №2 is 444 cycles, spike №3 is 937 and so on. Obviously it is tendency of initial distance between spikes increasing (up to spike №3) with following spikes compaction (spikes recognizing become more sophisticated for №№8-10).

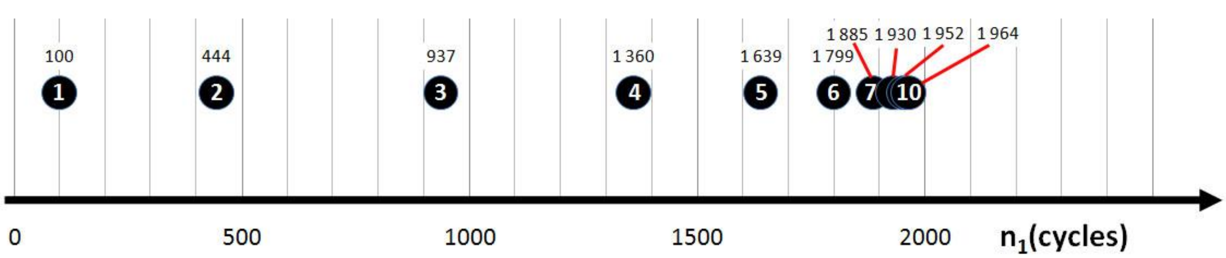


Fig. 5. Graphical representation of V.Ivanova recurrent dependence for explicit series

- series of spikes origin can be explained by microplastic deformation process in diferent grains on certain oriented plane;
- metals fatigue process should be considered as a *composition of two processes*: high-frequency process on a nanoscale level (within a separate slip plane of grain) and low-frequency that is proceeding on mezo- and macroscale levels.

So-called *high-frequency process* is caused by fatigue process bifurcation points in various crystallographic planes and it is characterized by spikes.

Tests have shown that discrete spikes for every stress level organize a totality of few cascade of series.

For example, on the Fig. 6 three series with 4 spikes are shown: I-series (blue ■) II-series (green ▲) and III-series (red ●). On diagram $n_{2\,0}$ is mean value of results with follow condition: the specimens are tested only under σ_2 stress level or, in other words, with n_1=0.

For every series it is possible to find appropriate spikes in n_1-n_2 diagram. But for I-series and III-series spikes №4 haven't coincidence with correlation field spikes by reason of tests absence with appropriate n_1, and the same situation with single spikes S_1, S_2, S_3: a lack of test data makes it impossible to find other spikes according to Eq.1.

Phenomenon of high frequency process is conformed plastic deformation evolution at different scale levels in according to V.Panin's theories [4,5].

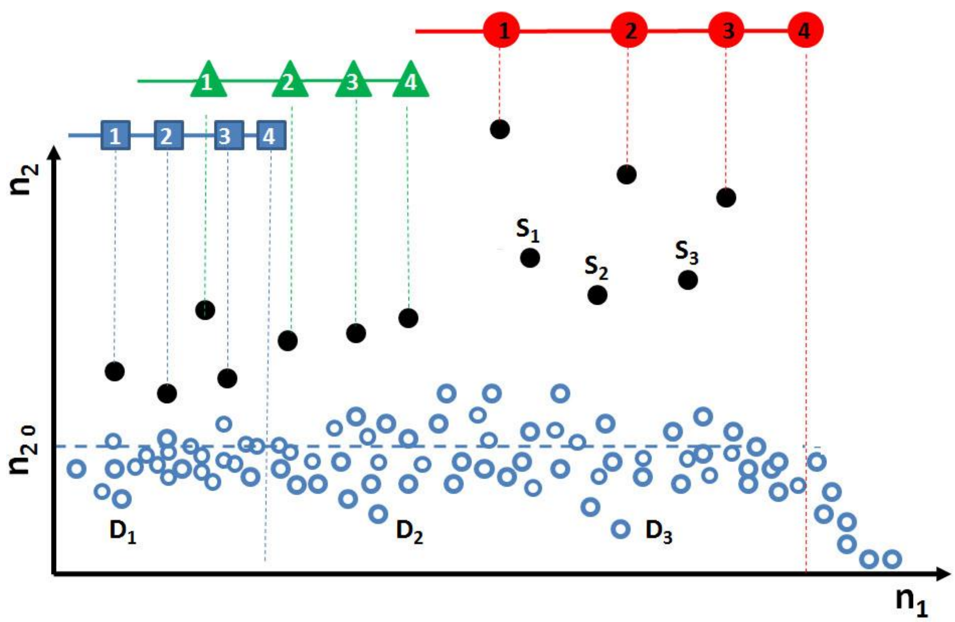


Fig.6. Conventional correlation field for prior cyclic loading – residual durability

Now, in more details the *low frequency process* of metal evolution that is caused by successive defect substructure changes will be considered. On Fig. 6 data points of low frequency process are marked by bubbles (○).

During low frequency process it is carried out principles of successive, selforganize substructure realization by reason of definite microplastic deformation scale level achievement [5].

Metal fatigue behavior under low frequency process is described by many authors as stages of fatigue. Mechanism of substructure evolution has been well studied experimentally and by instrument methods [3].

Evolution rearrangement of defect structure under microplastic deformation process flows in according to synergetic principles at the micro-, meso- and macroscale levels. This rearrangement allows to mark out system of fatigue process stages and use generalized S-N curve. Number and length of stages depend on stress level (Fig.7).

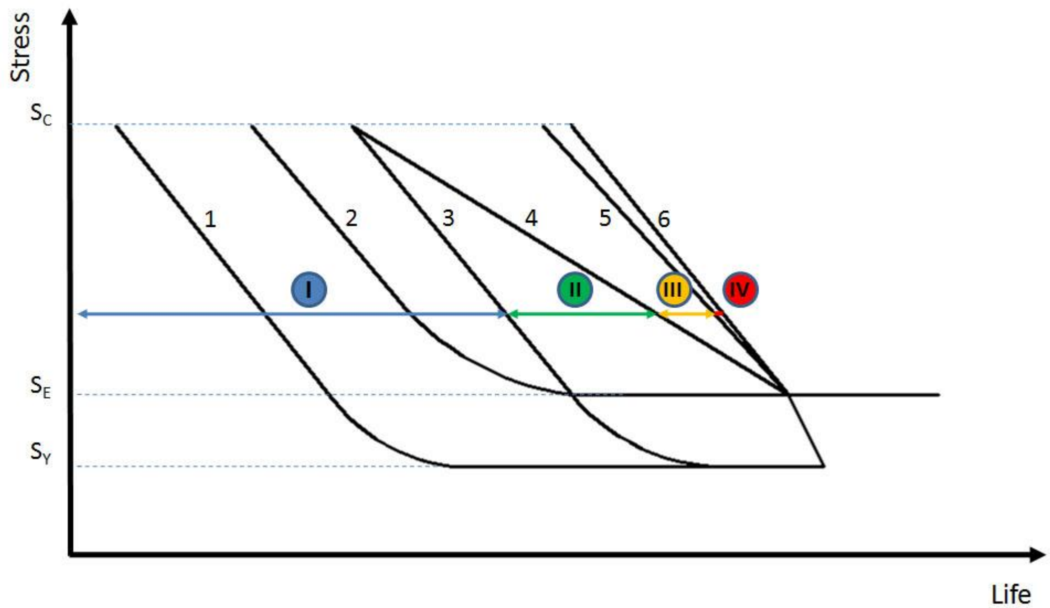


Fig.7. Generalized S-N curve diagram [3]

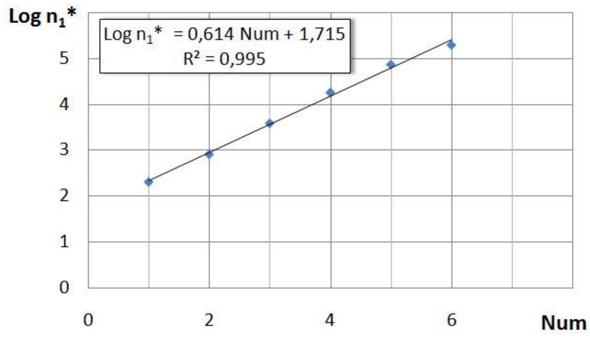
1 – Line of cyclic flow beginning; 2 – Line of cyclic flow ending; 3 – Line of submicrostructure crack initiation; 4 – Line of microstructure crack initiation (French line), 5 – Rupture line, 6 – S-N curve; S_C – critical fatigue stress; S_E – endurance limit; S_Y – cyclic yield stress; I – crystal lattice damage accumulation; II – metal discontinuity that is connected with submicrocracks initiation; III – from micro to macro crack propagation; IV – rupture.

In our case material residual durability research tests showed some characteristic fatigue intervals. Theses intervals boundaries are characterized by minimum residual durability n_2* or "drops" (D_1, D_2, D_3 on Fig. 6).

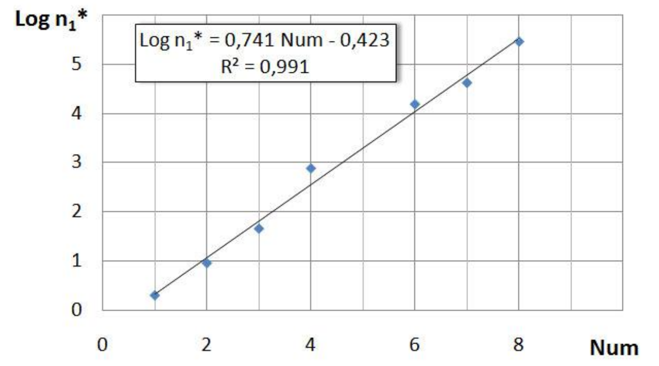
In our opinion, it is necessary to pay attention especially to these points. Analysis of low frequency process test result shows close correlation between number of prior cyclic loading up to drops (n_1*) and their position numbers (Num) in correlation field.

On application of copper and 12H18N10T correlation fields for each drop was set position number from 1 to 6 for copper (Fig. 3) and from 1 to 8 for steel (Fig. 4). The results of position number and n_1* relationship are shown on Fig. 8 on semilog diagrams.

Having correlation field it is possible to obtain the correlation function for prior cyclic loading and residual durability results. But accuracy of this dependence is low and can lead to considerable errors. In our opinion, it's more reasonable to use low part of correlation field envelope that is geometrical place for results points of metal residual durability in the absence of hardening at slip plane.



a



b

Fig. 8. Position number and log n_1* relationship for copper (a) and 12H18N10 (b)

Further correlation field envelope low part researches will make it possible to increase accuracy of residual durability prediction and decrease safety factor value.

Summary

Fatigue process dividing on evolutional (low frequency) and discrete (high frequency) processes is conditional, but it is more convenient for analysis. In general, correlation field represents evolution process at different scale levels.

For practice purpose our results about prior cyclic loading - residual durability correlation field could be used in next ways:

1. It will be defined a variant of trend line for n_1-n_2, expected that it will be monotonic and could be described by one of existing function. In this case relations will have extremely low coefficient of determination R^2. The cohorts of researcher deem that durability spikes are random test errors and it is possible to ignore them for next calculations.
2. It takes into account that durability spikes are represented real process in metal and fatigue process could be described as component of high and low frequency process. Excluding of high frequency process data allows to obtain n_1-n_2 dependence, that will describe residual durability changes initiated by rearrangement of defect structure under cycling loads.
3. Low part of correlation field envelope that represent minimal residual durability value will be used. It's the most conservative method of residual durability assessment and allows to decrease value of safety coefficients.

According to the chosen method of residual durability estimation different nondestructive methods could be selected.

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