DETECTION OF A FATIGUE CRACK BY METHOD OF AN ACOUSTIC EMISSION

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Abstract

The suppositions on AE conformity to phases of fatigue fracture development are made at the base of AE process formation self-similarity postulate and of one of microcrack system configuration stability at the polycrystalline material. The calculations under the offered model do not contradict experimental data obtained at the aluminum alloy.

1. Introduction

The method of acoustic emission (AE) is distributed rather broadly in practice of the airframe technical state control /1-5/. One of major virtues of this method is the direct connection of fixed signals with irreversible processes of strain and fracture, happening at the inspected material. The AE method allows to fix in time dynamic phenomenon, happening at the material, rather precisely. In many situations the modern systems of measurement allow also to determine coordinates of a stimulus source of dynamic disturbances with the adequate accuracy. The main difficulties of the AE signal analysis are connected with the interpretation of the results of measurement. The precise identification of separately taken AE signal to one's source, nature of phenomenon, happening at the material, and quantitative characteristics of intensity of this phenomenon is the complex scientific and technical problem. In this connection, the use of AE method in scientific and applied problems has some perspective directions. One of such directions is the approach based on use of the model description of some characteristics of object of research with consequent check on conformity to the results of experiment.

Some aspects of AE method application to study the phenomenon of the aluminum alloy fatigue fracture are considered at the present article. Main purpose of research is the determination of the connection between the character of AE change and the phases of fatigue fracture development.

2. Material, samples and modes of tests

The experimental research was executed using the sheet samples of thickness 2.5 mm and of the working part width 100 mm at cyclical tension. The sample material is the aluminum alloy D16T. The mechanical characteristics are: ultimate strength - 435 MPa, yield limit - 280 MPa, unit elongation at rupture - 11 %, relative narrowing - 26%.

The notch was made at the sample working part lateral side in order to localize the zone of the intensive fatigue process. The notch depth is 11 mm, its bottom radius - 0.5 mm. The calculation by the boundary element method allowed to determine, that the stress concentration factor is equal to 11.4. The preliminary analysis of the sample stress-strain state has allowed to receive the quantitative evaluations of the zone of probably most intensive fatigue process characteristic sizes. The value of maximum principal stress is not less than 90 % of maximum circumferential stress at the critical point in the zone of following characteristics: the angle of the concentrator contour arc is 45°, size in direction of the curvature radius – 2 mm.

The following characteristics of variable stresses in the sample cross section far from the concentrator are selected: maximum stress of the cycle - 80 MPa, minimum stress - 40 MPa. The stress cycle ratio is selected large in order to eliminate the influence of the crack surface mutual friction processes when it's closing on the acoustic emission. The quantitative characteristics of stresses are selected so, that the macroplastic strains appear in the neighborhood of the concentrator top at the first cycle, but the strain should be purely elastic at the consequent cyclical load.

Frequency of variable load is about 13 Hz.

The computational evaluation of fatigue life before the macrocrack origin is received approximately 2×10^4. Taking into account effect of influence of the strain field considerable non-uniformity in the concentrator critical zone, it is possible to expect, that the real fatigue life before the fatigue crack origin is about 30-50 thousands of cycles.

The continuous observation of the sample surface at the notch neighborhood was executed with the aid of microscope of tenfold increase during fatigue tests. The moment of fatigue crack of length 0.5mm appearance and also its consequent propagation were fixed. The AE piezo-electric receiver was placed on the sample surface at the point of (10 mm, 10 mm) coordinates relative to the notch top. The AE total account and intensity were continuously fixed during the tests. The AE signal fast record the oscillograph fillet was also periodically made synchronously with the operational load.

3. Some main results of tests.

The generalized view of the main results of tests necessary for this work purposes are given on figs. 1 and 2. The diagrams of the relative total AE dependence on the relative number of the variable load cycles for two samples are shown. Here N_{aek} and N_k are total AE value and number of the variable load cycles accordingly at the moment of the test finishing, i.e. when crack length close to the critical one. The characteristics of AE, of cycle number N (expressed by kilocycles) before the fatigue crack of length 0.5 mm appearance, and also of the cycle number N_k before the finite length L_k reaching by crack are shown in table 1.

Table 1. The characteristics of AE, of cycle number N (expressed by kilocycles) before the fatigue crack of length 0.5 mm appearance, and also of the cycle number N_k before the finite length L_k reaching by crack

The sample number	L_k, mm	N, kc	N_k, kc	N/N_k	N_{ae}/N_{aek}
1	17.6	67.2	85.7	0.784	0.512
2	21.0	83.5	118.5	0.705	0.488

The primary analysis of given results allows to conclude, that 45 - 55 % of total acoustic emission correspond to the stage of macrocrack origin. Thus the total AE change depending on the variable load cycle number is of the complex structure. It is qualitatively similar for various samples. It is obviously connected with the complex character of the fatigue damage accumulation in material.

The determination of AE change regularity connection with changes of material allows to use AE in scientific researches on the problems of material fatigue, and also of evaluation of the machine element detail material state at variable operating load more effectively in perspective.

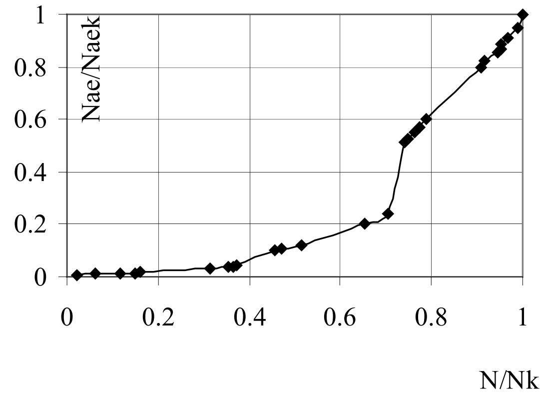

Fig.1. Sample 1

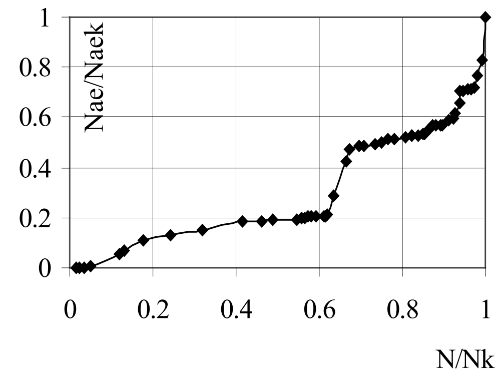

Fig.2. Sample 2

4. Connection of the fatigue crack length with total acoustic emission and the self-similarity hypothesis

The stage of the visible fatigue crack growth is simpler for the interpretation of AE origin. The real area of fracture surface can be accepted as the criterion of material damage at this stage. It is proportional to the crack length at the first approximation (if the sample is of constant thickness). The relations of AE relative increment at the stage of crack growth on the crack length (in relation to finite values) are shown on figs.3 and 4 for two samples. Experimental curves have definite deviations from linear relation. But the absence of any stable regularity for three samples testifies with high probability that these deviations are of random character. Therefore it is possible to consider that the supposition on the again derived fracture area surface proportionality to the appropriate AE increment is acceptable with certain accuracy. It means, that the new fracture surface unit formation is accompanied by approximately identical AE increment independently on the stage of fatigue crack development. It is important to emphasize that the rate of crack propagation varies by several degrees when change of crack length from the initial size up to critical one. The fracture mechanism also varies. However, total AE per unit of again derived surface remains approximately constant. Therefore the attempt to use this property for explanation of microcrack formation and propagation regularities is made in the present work.

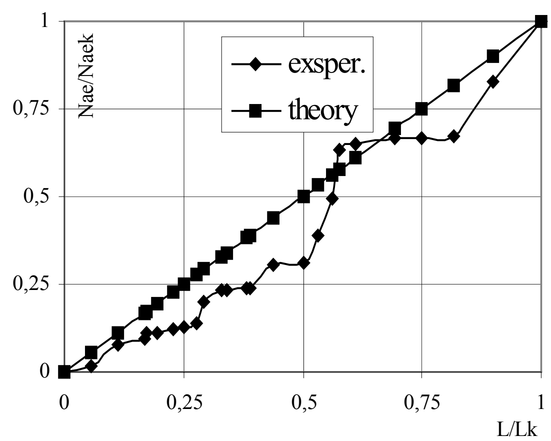

Fig.3. Sample 1

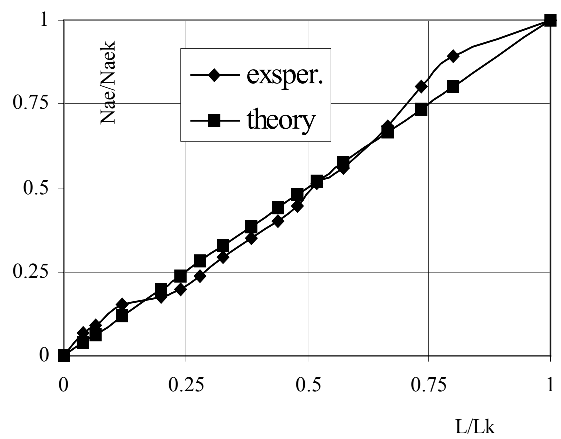

Fig.4. Sample 2

It is known that AE can be conditionally classified on continuous and discrete AE. Continuous AE is of small intensity, but it is displayed at occurrence of no matter how small plastic strains /7/. Discrete AE is displayed in certain rather short periods and it is of large intensity, which is the indicative of the explosive release of fair quantity of elastic strain energy. Every one of these kinds is connected with certain types of sources. Many of these sources generate both AE kinds, as it is supposed. However, it is represented, that the main source of continuous AE is the irreversible motion of dislocations at the material plastic strain, and discrete AE is mainly connected with the material fracture and with the new surface formation. Therefore it is possible to offer the simple mechanical model of continuous and discrete AE formation. This model can be explained by considering of the material elementary volume strain diagram at half-cycle of the load increase. Every small load increment causes the small strain increment and appropriate plastic strain increment. The AE increment will be proportional to appropriate plastic strain increment. AE of small intensity will also continuously increase during monotone load increase. The sudden fracture of elementary volume accompanied by momentary release of the considerable amount of elastic energy takes place when reaching of limiting stress. The discrete AE is connected with this energy.

There is the sensitiveness threshold of AE recording apparatus. Its order when continuous and discrete AE is different. The intensity of continuous AE is usually lower than the discrete AE threshold. Continuous AE is filtered together with other noise of small intensity in such tests. Therefore the discrete AE only is registered. According to offered model it is proportional to the gap new surface area.

Summarizing, it is possible to formulate the basic postulate for construction of model of AE and the fatigue fracture process mutual connection. Conditionally it is called as the discrete AE self-similarity postulate. Its essence is the following: total discrete AE is proportional to the total area of again derived gap surfaces in material independently of the fatigue process development stage.

5. Some main regularities of polycrystalline constructional material fatigue fracture. The microcrack interference and stability postulate

Polycrystalline environment of modern constructional metal materials is the combination of elementary structural units - grains. The ordered arrangement of atoms (crystalline grille), and also brightly expressed anisotropy of the mechanical characteristics are characteristic of grains. The principal axes of the mechanical characteristic symmetry are of random orientation with close to equiprobable distribution in space in the hardened polycrystalline material structure. Therefore polycrystalline material behaves practically as isotropic one in standard tests. However, the real load distribution among the grains (stress of the second kind) is essentially heterogeneous. The grains of largest modulus elasticity in the operational load direction perceive the largest load when the same macroscopic strain. The sliding processes start in these grains at earlier stages.

The grain-dividing surface is also important for strain and fracture processes. It is named as the boundary. The regulated crystalline structure is systematically broken at the boundary, the release of substance other phases takes place there. Because of this, the mechanical properties of material at the grain boundary can be essentially different in comparison with basic material. The presence of boundaries and grain different orientation are the obstacles to the sliding distribution and microcrack propagation between the grains.

The material fatigue process develops when variable stress, as it is known. The intensity and character of fatigue damages depends on the operational stress level. If these stresses do not call macroscopic plastic strains, but exceed the material fatigue limit, then this is the high-cycle fatigue area. All further considered regularities and the analysis results concern just to this fatigue area.

The initial stage of fatigue process is named as incubation period. There are no noticeable irreversible changes of grain structure at this stage. Then changes are found out in some grains, which are going out to the sample surface. The number of sliding lines in due course is increased, their join to sliding bands takes place. Part of these sliding lines and sliding bands reaches the boundary and their further development is blocked. The sliding process in grains is heterogeneous one. The sliding is not observed at the considerable part of grains. It testifies about unfavorable orientation of this part of grains in relation to the operational stresses for sliding development. The direction of primary orientation of sliding lines and bands at the surface is precisely expressed. It is perpendicular to the maximum stress direction. The sliding bands are also approximately mutually parallel within one grain, and the tendency to sequence of long and short bands is visible. The overcinking of grain boundaries by most developed sliding bands and their join to the analogous bands of other grains take place at the following stage of fatigue process development. As the result of it the microcracks of length equal to 2 … 3-grain sizes at the surface are formed. Obviously, that the process is inspected by regularities of the microcrack load-carrying interaction and it is finished by one turnpike crack formation.

The second postulate of the basis of the fatigue model process, is called as a postulate of stability: during the fatigue development the system of microcracks sequentially passes a number of steady configurations determined by regularities of the interference, and the final configuration is one active crack called as the turnpike crack.

Microcrack mutual influence or interference determines the stability of the microcrack configuration. The basic singularities of the crack interference phenomenon can be revealed, considering a system of two collinear or parallel through cracks at the elastic plate in homogeneous field of stresses. Two collinear through cracks form the first system. Obviously, that steady final configuration is one crack formed after confluence of two initial cracks. It follows from character of relation between the stress intensity factors for the near ends of cracks and the distance between them: the increment of one crack results in increase of the stress intensity factor (and so, in the rate of crack propagation) for the near end of another one.

The second initial system is formed by two parallel through cracks of equal length. Obviously, that steady configuration is one, for which the increment of one crack length lowers the stress intensity factor of another crack. The «competitiveness» of cracks takes place during their growth. As the result of it the growth of one of them is suppressed.

6. Model of fatigue fracture process development

In order to receive the AE quantitative estimate at the various stages of fatigue process development corresponding to the self-similarity postulate it is necessary to know an estimate of change of the microcrack surface area. The model of fatigue fracture development is considered with this purpose. Let there is a zone of maximum stresses on the sample surface, where the state of stress is like the homogeneous one. Further it will be named the critical zone because the fatigue damage of material within this zone happens most intensively.

The first stage of the high-cycle fatigue development is the incubation period of sliding. The bands of sliding are practically absent on the surface during this stage. It is supposed that only the continuous AE of small intensity can be present at this stage. This AE is filtered together with other weak noise by proper selection of the recording instrumentation sensitivity threshold. The similar situation was in the experiment executed.

The crystallographic orientation of some grains is favorable for development of bands of sliding. This process takes place in these grains at the second stage. Obviously, that number of grains where the sliding processes are developing is the more, the higher is level of variable stresses σ. The degree of surface damaging in the critical zone of sample can be evaluated by the relative portion $\rho(\sigma)$ of grains, where the microplastic strain develops under the variable load action. It is possible to assume, that it is the monotonically growing continuous function, which is equal to zero when some minimum damaging stress σ_0, which is lower than the material fatigue strength σ_r and achieves the one when stresses near the cyclical yield limit σ_y.

$$\rho(\sigma)=\begin{cases} 0, & \sigma \le \sigma_0 \\ 1, & \sigma \ge \sigma_y \end{cases}, \tag{1}$$

The different number of bands (from several ones up to several tens) of various length and density of the sliding line can appear in one grain.

Their average $n_0(\theta_1,\theta_2,\sigma)$ depends on the grain angular orientation θ_1, θ_2 corresponding to directions of maximum principal stress and of the surface normal, as well as on the stress value σ. As it was mentioned, the bands of sliding are blocked by the grain boundaries when stresses lower than the yield limit. Therefore the fatigue fracture processes develop within the grains as discrete and isolated for a long time. The microcracks form and grow in the most developed bands of sliding. The most possible number of cracks in the separate grain does not exceed number of derivated bands of sliding n_0. While the microcrack depth is small on a comparison with the grain sizes, the number of microcracks can be large. At early stage of fatigue process development the parallel microcracks develop in the grains damaged by bands of sliding, and besides the mutual influence of cracks will be poorly appreciable up to the mean size about $l_0=d/(2n_0)$. The total area of the fatigue crack surface A_0 in the grain to this moment is

$$A_0 = ndl_0 = \frac{d^2 n}{2n_0}, \tag{2}$$

The following step of the grain loosening is that the growth of the half of microcracks stops, and another half remains the active one. The total increment of its crack surface is $\Delta A_1 = \frac{nl_0}{2} = \frac{A_0}{2}$. On the following step number of active cracks is $n_2 = \frac{n_1}{2}$, and the mean increment of the crack length before reaching a new unstable configuration is $2l_0$. The total increment of the crack surface is $\Delta A_2 = n_2 2l_0 = \frac{n2l_0}{4} = \frac{A_0}{2}$. In general case the crack number is $n_i = \frac{n_{i-1}}{2}$ on the step i, and the mean increment of the crack length before reaching a new unstable configuration is $2l_{i-1}$. In the issue it results in the increment of the crack surface $\Delta A_i = \frac{A_0}{2}$. Corresponding to the considered scheme the process of grain loosening represents the successive realization of the active fatigue microcrack unstable configurations. The number of microcracks decreases approximately under the law of geometrical progression with denominator 0.5, and the mean depth will increase under the same law with denominator 2. The process is finished after k steps by formation of one microcrack which is going out to the grain boundary, i.e. reaching size $l_k = 2^k l_0 = 2^{k-1} d/n_0 = d$. It follows, that

$$k = 1 + ln\,(n_0), \tag{3}$$

The total area of microcrack surface forming at the stage of one grain loosening, approximately is

$$A = k\frac{A_0}{2} = \frac{[1 + ln(n_0)]A_0}{2} = \frac{[1 + ln(n_0)]d^2}{4}, \tag{4}$$

Obviously, that at the end of the stage of isolated grain loosening the total area of microcrack surface is

$$A_1 = \frac{[1 + ln(n_0)]d^2}{4} m_0 , \tag{5}$$

where $m_0 = \rho(\sigma)\ S/d^2$ - number of damaged grains, going out on a critical surface S.

Because of the parallel crack negative interference it is probable, that the considerable number of microcracks will be formed in the grain till the end of the second stage, but only one of them, the greatest one remains active. The other microcrack propagation within the given grain ceases. The microcrack growth is blocked on the grain boundary. It provides the prolonged stability of the configuration, when the microcracks are limited by the grain sizes.

After certain period of delay the microcracks will begin to overcome the boundaries of grains. As a first approximation it in possible to accept, that before reaching the size $l_1 = \sqrt{\frac{S}{2m_0}}$ (the characteristic size of surface come on one half microcrack) of mutual influence of microcracks will not be. Thus the additional grain (increment) of an area of surface of microcracks will make $\Delta A_1 = m_0(l_1^2 - d^2)$. To the end of the second stage the system of active microcracks with the mean characteristic size l_1 and approximately same mean distance (span) between them is formed. It is accepted for simplicity, that they will form the periodic system of one of two types. In both cases there are $k_2 = \frac{b}{l_1}$ rows of microcracks within the critical zone with $k_1 = \frac{a}{2l_1}$ microcracks in each row. Thus it is possible to accept, that the microcracks do not render mutual influence.

The third stage. After definite operating time the microcracks begin to overcome the grain boundaries both on a surface, and in the depth of material. The confluence of collinear cracks begins. The processes of their interference adjust the formation of new steady configuration: if the confluence of adjacent collinear cracks takes place in one row, it results either in complete «braking» of near microcracks in adjacent rows (first version), or in «braking» of their ends falling to the interference zone (the second version). In the first version the part of microcracks completely fallen to the negative interference zone, stops their growth, i.e. are transformed into passive microcracks. The account of expected number of microcracks in the second version is executed. Number of microcrack rows is k_2 and it does not change, but microcrack number in one row is $k_1/2$, so the system of microcracks of length $3l_1$ and of the total number $m_1 = \frac{k_1 k_2}{2}$ will be formed to the end of the stage. Supposing, that the crack also additionally sprouts for the depth of one grain to the depth of material, it is possible to evaluate additional increment of its surface $\delta A_1 = (1 + 3)l_1^2$.

During the process of microcrack further confluence the size of interference zone will increase proportionally to the microcrack size increase. The intermediate steady configurations with the passive microcrack number increase and active microcrack number decreasing will be formed. On a comparison with the previous steady configuration the active microcrack number in one row and number of rows decrease twice. As the result, total of active cracks becomes equal to $m_2 = \frac{k_1 k_2}{2^3}$ and additional increment of its surface $\delta A_2 = (2 + 7)l_1^2$.

As the result of similar reasoning, it is possible to receive, that at the stage of formation of **i** - number steady configuration, number of active cracks becomes equal to

$$m_i = \frac{k_1 k_2}{2^{2i-1}} , \tag{6}$$

and the additional increment of its surface can be evaluated under the formula

$$\delta A_i = 3(i+1)l_1^2 \,, \tag{7}$$

The process of the microcrack confluence, as well as the third stage as a whole, is finished at the step ***n*** by formation of one turnpike crack.

If accept $m_i = m_n = 1$ in the formula (6), it is possible to receive

$$n = sup\left[\frac{1}{2}\left(1+\frac{\ln m_0}{\ln 2}\right)\right], \tag{8}$$

where ***sup(x)*** is the ***x*** upper whole boundary.

All the aforementioned allows to evaluate the total area of fatigue microcrack surface formed at the stages before the turnpike crack formation.

$$A = A_0 + \Delta A_1 + \sum_{i=1}^{n} \delta A_i \,, \tag{9}$$

Corresponding to the hypothesis of self-similarity total AE to the moment of origin of fatigue macroscopic crack of definite length should be proportional to the fatigue microcrack surface total area ***A***.

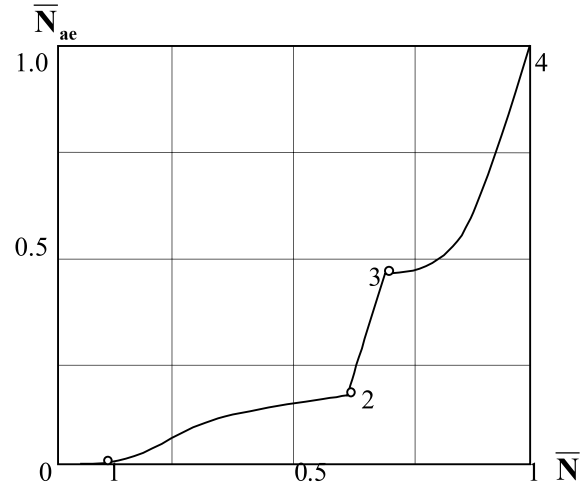

Fig.5: The scheme of relation of relative total emission to the relative number of cycles of variable load

The relation of relative total emission to the relative number of cycles of variable load is schematically submitted in fig.5. It is possible to allocate some characteristic sites on the schedule, which are identified by various phases of the fatigue process as follows.

The site 0-1 corresponds to incubation stage, when there are no processes of sliding and destruction with intensity, sufficient for AE excitation.

The site 1-2 corresponds to stage of development of sliding and microcrack formation processes mainly within the limits of separate grains at the critical zone of the sample surface with interlock of microcracks by the boundaries of grains. The AE intensity at this stage is rather insignificant, but AE total value is the significant part of common AE at the end of tests. The cause of it is, that the AE sources (microcracks, formed in separate grains) are rather weak, but because of their large number total AE at the end of stage is of significant value. Pursuant to this model the system of microcracks of the common surface (the formula 5) is formed at the end of the isolated grain loosening phase (the site 1-2).

The site 2-3 corresponds to the stage of the grain boundary intensive overcinking by microcracks and their confluence. It was shown earlier, that the fast confluence of microcracks accompanied by the strain energy intensive release takes place because of strong positive interference of collinear microcracks after overcinking of the grain boundaries. The significant part of this energy will be transformed to the kinetic energy of the environment motion. The total area of surface of fatigue microcracks derived at phases up to the turnpike crack formation is evaluated by formula (8). The quantity of microcracks steady configurations formation is evaluated by formula (9).

The process is finished by formation of one turnpike crack and termination of growth of remaining microcracks fallen to the zone of negative interference. During rather short interval the significant part of total AE for all time before fracture is fixed. After the turnpike crack formation total AE growth rate sharply decreases.

The site 3-4 corresponds to stage of the turnpike crack growth before reaching its critical size. As the result of growth rate increase total AE growth rate will also increase.

Using the initial data for conditions of experimental research realization, it is possible to conduct an evaluate the surface cracks total area under the offered model process fatigue development for some characteristic points of AE dependence on number of cycles (in particular for points 2 and 3). Therefore it is accepted, that $\boldsymbol{S = ab} = 5\times2 = 10$ mm^2, the crack length at the moment of tests stop is $\boldsymbol{Lk}$ = 15 mm. The remaining parameters varied in the following limits: $\boldsymbol{\rho(\sigma)}$=0.05…0.65, $\boldsymbol{n_0}$=10…80, $\boldsymbol{d}$=0.05…0.1 mm.

The results of calculations of the surface cracks relative area $\overline{A}_2$ and $\overline{A}_3$, appropriate to points 2 and 3 of dependence $\overline{N}_{ae}$ (fig.5), are submitted in table 2.

The boundaries of change of the relative rated area $\overline{A}$ for range of parameters $\rho(\sigma)$, n_0, d change assumed in calculations are indicated in table 2.

Table 2. Comparison of the cracks area calculation data to the AE experimental data

Number of points	**Relative acoustic emission $\overline{N}_{ae}$**		**Relative rated area of the crack $\overline{A}$**
	Sample 1	**Sample 2**	
2	0.234	0.209	0.248 … 0.272
3	0.512	0.489	0.508 … 0.572

Comparison of the cracks area calculation data to the AE experimental data allows to make a conclusion on consistency of offered model of AE connection with fatigue damages. At the same time, the experimental researches should be continued. In particular, it is desirable to execute the direct research of material microstructure at the considered alloy in the critical zone of surface in order to fix the real view of fatigue fracture process at the broad range of stresses.

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