

# Acoustic Emission Monitoring of Fatigue Crack Origination during Titanium Specimens Tests

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**Abstract.** The titanium alloy VT3-1 has been used in fatigue tests. During the tests, there were performed Acoustic Emission monitoring. The main idea of the crack detection in fatigue tests is based on the introduced earlier “ $\alpha$ -criterion”. “ $\alpha$ -criterion” - break in the graph line that represents the total acoustic emission dependence on the number of loading cycles. After the fatigue test of specimen, it was subjected to monotonic tension up to the fast fracture.

**Key words:** acoustic emission, fatigue crack, specimen test.

## THE MODEL OF QUANTITATIVE EVALUATION OF FATIGUE CRACK GROWTH SPEED

In the process of cyclic loading, as it is known, there are happening irreversible material structure changes. At the present time it is universally adopted that fatigue damaging process is connected with the development of plastic deformation preparing the rise of submicrocracks. They gradually grow up and turn into microcracks which further on increase up to the size of macrocracks visible to the naked eye.

According to kinetic durability conception [1], each act of deformation or destruction is accompanied by the rupture of interatomic connections with release of some energy.

The accumulation of the damages and the collective rupture of the interatomic connections may initiate an acoustic pulse sufficient for its registration by the converter. Therefore, each act of material structure damage is corresponded by a primary resilient pulse, the process of radiation of which presents a so called “AE act”, and measuring AE act sequence speed will allow to evaluate destruction process going speed.

Let's assume that AE pulse number generated during a cycle, is proportional to that part of potential energy U released at the progress of the crack in this U potential energy cycle, which turns into  $A_k$  kinetic energy of environment movement causing a reaction of AE signal converter. The presence of a definite connection between the kinetic energy radiated at the crack progress, and crack growth speed, was determined on the basis of the following analysis: Let crack surface receive in a certain loading cycle  $\delta S$ . This crack increment causes potential energy release [2, 3].

$$\delta U = \frac{1-\mu^2}{E} K^2 \delta S \quad (1)$$

Where E – material resilience module,  $\mu$ - Poisson coefficient, K – tension intensity coefficient (TIC) (it is supposed that the crack develops according to normal separation mechanism).

The energy released goes in part for material plastic deformation connected with the advancement of the plastic

area. This share of energy is proportional to the volume of the layers plastically deformed, immediately adjoining newly formed surface.

$$\delta A_p = \bar{\sigma}_i \bar{\varepsilon}_i + 2h\delta S \quad (2)$$

Where  $\bar{\sigma}_i$  and  $\bar{\varepsilon}_i$  - average tension and deformation intensities in the layers specified, 2h – layer thickness

If to assume an extent dependence of stretching diagram of the following kind:

$$\sigma_i = \sigma_0 \left( \frac{\varepsilon_i}{\varepsilon_0} \right)^m,$$

where m- strengthening index,  $\sigma_0$  – yield point, and  $\varepsilon_0 = \sigma_0/E$ , then deformation intensity distribution in the plastic area in dependence on r distance from the top of the crack might be approximated with the expression:

$$\varepsilon_i(r) = \varepsilon_0 \left( \frac{r_p}{r} \right)^{\frac{1}{1+m}} \quad (3)$$

where  $r_p$  – plastic area size.

As a result, we shall determine average values of plastic area tensions and deformations according to the expressions

$$\bar{\sigma}_i = \frac{1}{r_p} \int_0^{r_p} \sigma_i(r) dr = (1+m)\sigma_0 \quad (4)$$

$$\bar{\varepsilon}_i = \frac{1}{r_p} \int_0^{r_p} \varepsilon_i(r) dr = \frac{(1+m)}{m} \varepsilon_0 \quad (5)$$

As  $h \sim r_p$ ,  $\delta S = t\delta l$ , then using (2), (4), (5), we receive for a plate of t thickness

$$\delta A_p = \beta \frac{(1+m)^2 \sigma_0^2}{m} r_p t \delta l \quad (6)$$

Where  $\beta$  – a constant,  $\delta l$  – crack length increment  
For approximate estimate we shall assume [4]

$$r_p = \frac{K^2}{2\pi(1+m)\sigma_0^2} \quad (7)$$

then

$$\delta A_p = \frac{\beta}{2\pi m} \frac{1+m}{m} t K^2 \delta l \quad (8)$$

If we put (1.1) and (1.8) into energy equation

$$\delta U = \delta A_k + \delta A_p$$

with subsequent transition to continuous functions on n cycle number, then as a result we shall obtain an expression for the determination of cycle kinetic energy

$$\frac{dA_k}{dn} = \beta_0 t K^2 \vartheta \quad (9)$$

Where  $\vartheta = dl/dn$  - microscopic crack growth speed equal to its progress in a specific cycle,  $\beta$  – a constant defined with an expression

$$\beta_0 = \frac{2\pi m(1-\mu^2) - \beta(1+m)}{2\pi m E}$$

Having assumed that Paris law is observed as well at little speeds of fatigue crack growth, if to take in it the average microscopic speed, then  $K$  may be expressed in the form of

$$K = \frac{1}{c} \vartheta^{\frac{1}{\alpha}} \quad (10)$$

Having assumed extent dependence

$$N_{\Sigma\Omega} \sim \left( \frac{dA_k}{dn} \right)^C \quad (11)$$

We shall get the sought for connection between AE summary count for a  $N\Sigma\Omega$  cycle and average microscopic speed of crack growth  $v$ .

$$N_{\Sigma\Omega} = \beta_1 \left( 1 - \beta_2 \vartheta^{\frac{2}{1+m}} \right) \vartheta^{\left(1+\frac{2}{\alpha}\right)} \quad (12)$$

where  $\beta_1$  и  $\beta_2$  - experiment defined constants,  $\alpha$  and  $C$  - constants of the material.

(12) dependence may be written in a simplified form

$$\vartheta = \frac{B}{r^C} N_{\Sigma\Omega}^{\frac{\alpha}{\alpha+2C}} \quad (13)$$

where  $B$  – a constant depending on resilient constants, strengthening index and Paris law constants.

The relation obtained practically should not depend on crack type, as the latter determines mainly the character of the plastic deformation. As to the destruction process and AE signals initiated by it in the material, the character of the rupture of the connections between the banks, when forming new crack surface, is determined only by the properties of the material.

In the model considered above (13) there appears such a parameter as summary AE in  $N_{\Sigma\Omega}$  loading cycle. Hence arises a question: Which loading cycles are to be taken into consideration when calculating crack growth speed by the summary AE in a loading cycle? There exists a theory that fatigue crack development is of step character. The beginning of these stages is determined by « $\alpha$ » criterion – the breaks on the diagram of the dependence of summary acoustic emission on loading cycle number. Therefore it may be supposed that when calculating fatigue crack growth speed, it is necessary to

take into consideration only those loading cycles, which fall to summary AE accelerated growth stages.

It is considered as well that the first « $\alpha$ -criterion» is the first break on the plot of the dependence of the total acoustic emission on the number of loading cycles - is one of the criteria of the arising of a fatigue crack when using AЭ method [5,6,7]. However it has not yet been proved up to this day that immediately after the specified criterion had been fixed on the acoustogram, there has formed a crack in the metal.

To corroborate these facts there were conducted fatigue tests of a number of samples of VT3-1 titanium alloy, strengthened from the surface, for investigating the mechanism of the arising of fatigue cracks and obtaining the correspondence of alpha criterion with the moment of the arising of a fatigue crack

#### TESTING METHODS AND THE USE OF THE EQUIPMENT

The titanium alloy VT3-1 has been used in fatigue tests. This type of material had after manufacturing procedure for compressors disks of aircraft engines Ultimate tensile strength in the range of 1040-1100 MPa with elongation and section area reduction respectively (10.8-16) % and (3.1-4.7) %.

Specimens for tests have been cut out from the disks of the second stage one of the engine compressor. Finally manufactured specimens has been subjected to heat treatment with tempering at  $T = 530^\circ\text{C}$  within 6 hours, and then cooling on air [8].

Round bar specimens of 8mm in diameter with circular notch of 2 mm in depth with stress raiser with concentration factor near to 1.46 have used in these experiments.

Specimens were then subjected to surface-hardening treatment with either hydraulic shot-peening by microballs with diameters in the range of (0.05-0.3 mm). The hardening degree was in the range of 1.1-1.27. Geometry of samples tested is presented on Fig. 1.

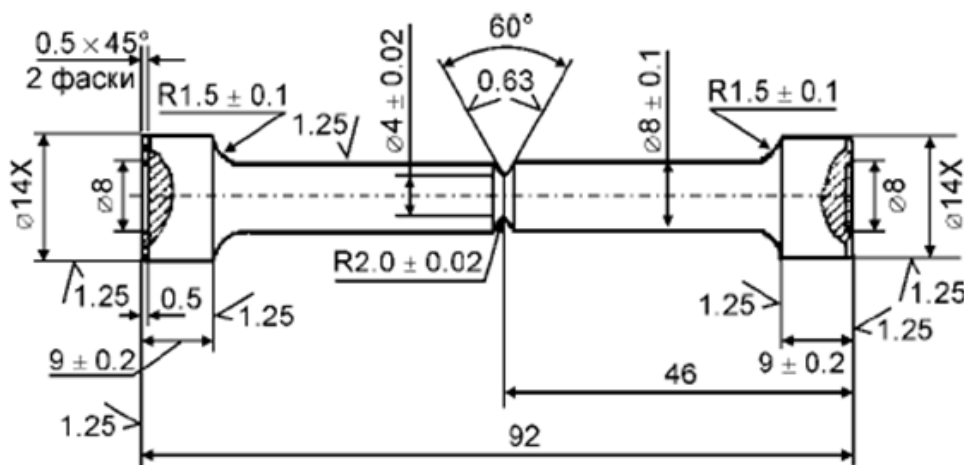


Fig.1 Geometry of samples tested

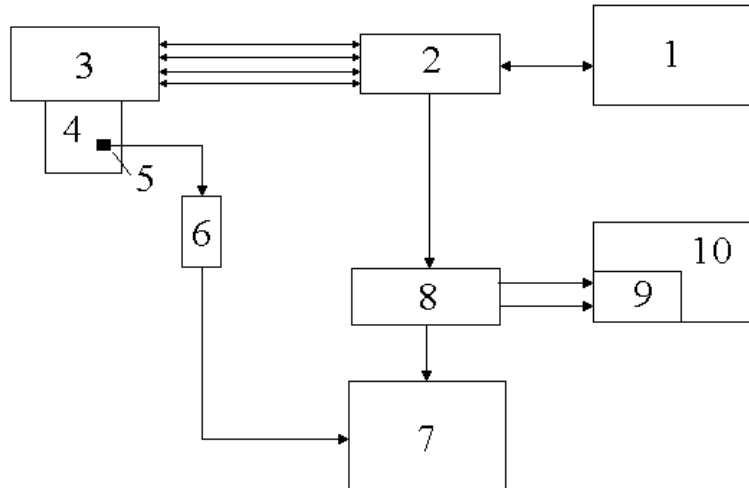


Fig.2. Measurement equipment connection diagram.

1 - Control system computer, 2 - Control system, 3 - hydraulic cylinder, 4 – titanium specimen, 5 - AE Transducer, 6 - prime amplifier, 7 - AΦ-15, 8 - matching device, 9 - ADC Lcard L-783, 10 - AE registering computer.

During the tests, there was performed AE monitoring for the registration of the moment of the fatigue crack origination. On Fig.2 there is shown a diagram of the connections of AE equipment for titanium specimens testing.

As an AE (5) sensor there was used a piezoelectric transducer. Signal from the AE transducer via the prime amplifier was brought to AF-15 (7) measurement complex. Further on AE formed pulses through a matching device serving for galvanic signal decoupling and AE pulse synchronization with loading parameters, are brought to ADC Lcard L-783 (9). For the synchronization of AE pulses with the load applied there was used a signal of strain gauge dynamometer U93.

For carrying out fatigue tests there was mounted a special unit, presented on Fig. 3. The unit consists of a frame, hydraulic cylinder for load setting, and strain gauge dynamometer (HBM, U93 type) for monitoring the load applied.

Cyclical fixed-sign load was applied to the samples being tested. Loading frequency for all the samples was 30 Hz. Applied load value for each specimen was corrected according to the results of the previous tests. Loading value for some titanium specimens are presented in Table 1.

For the purpose of the identification of the moment of abrupt increase of summary AE count at the cyclic loading with the changes of the inside structure of the material, sample testing was stopped after the registration of angles on the plot of the dependence of total acoustic emission on the loading cycle number.

After going through the fatigue testing unit, the specimens were subjected to monotonous tension up to the destruction. For this purpose, there was used a WPM testing machine worked out and finished at AVIATEST (see Fig.4).

After that there was conducted a fractographic investigation of the fracture. Specimen loading was carried out according to the movement along with the monitoring of the load applied.

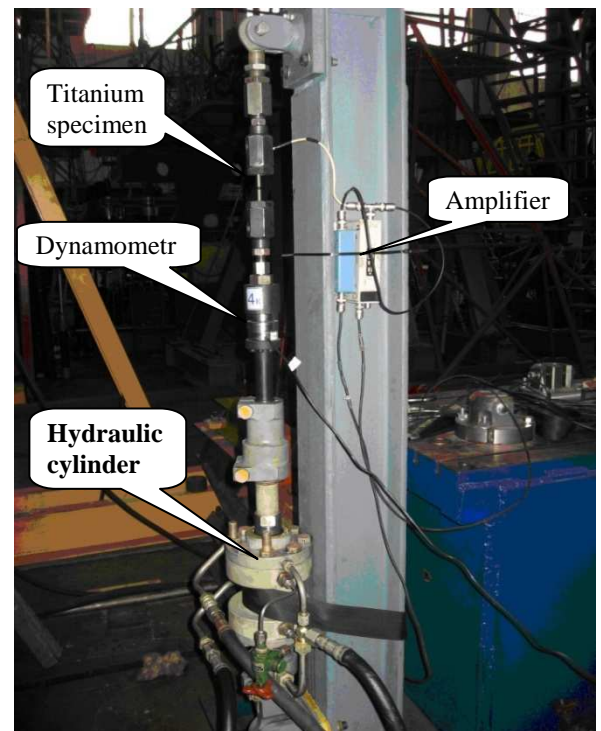


Fig.3 Titanium specimens testing unit

TABLE I  
 LOADING VALUE FOR TITANIUM SPECIMENS

Characteristic	Specimen №1	Specimen №2
Loading frequency, Hz	30	30
Maximal load, kN	5,65	5,27
Minimum load, kN	1,95	1,57
Mean load, κН	3,8	3,42
Load amplitude, kN	1,85	1,85
Asymmetry factor	0,345	0,298
Operating time, cycles	415104	4725809

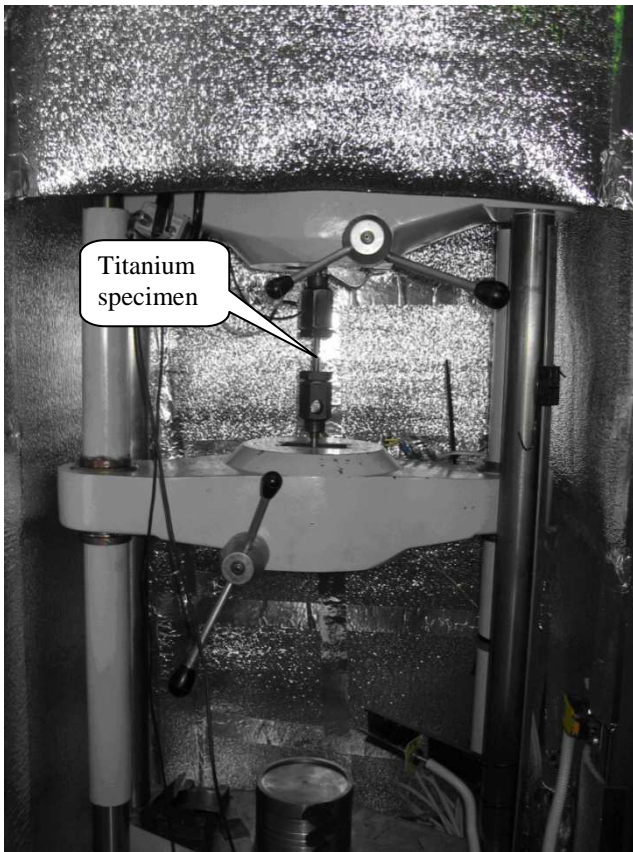


Fig.4 WPM testing machine

Sample tension speed was 0,005 mm/s for the tension process duration to be about 5 min. Such a little loading speed was chosen to give the material a possibility to react to the tension in all the areas where it had tension concentrators, and, first of all, where there had supposedly been formed the surface of a microcrack.

#### TESTING RESULTS

The results of AE control of the conception of fatigue cracks in the samples were presented in the form of plots of dependence of the total AE on the number of loading cycles, and fragments of synchronous record of AE signal intensity and the load applied.

Some of these plots are presented in Fig.5 and Fig.7. The results of the fractographic investigation of the fracture of these samples are presented in Fig.6 and Fig.8.

As a result of the fractographic investigation of sample fractures it was stated that in the samples there was formed a typical fracture with plastic deformation bevels, which is usually observed at elastic failure of samples being monotonously stretched. Flat elastic fracture in the middle and plastic deformation bevels along the surface of the sample. It was discovered that in the middle part of all the samples there had been formed a fracture relief with concentric pits. An analogous relief in the form of elongated pits was formed along the plastic deformation bevels.

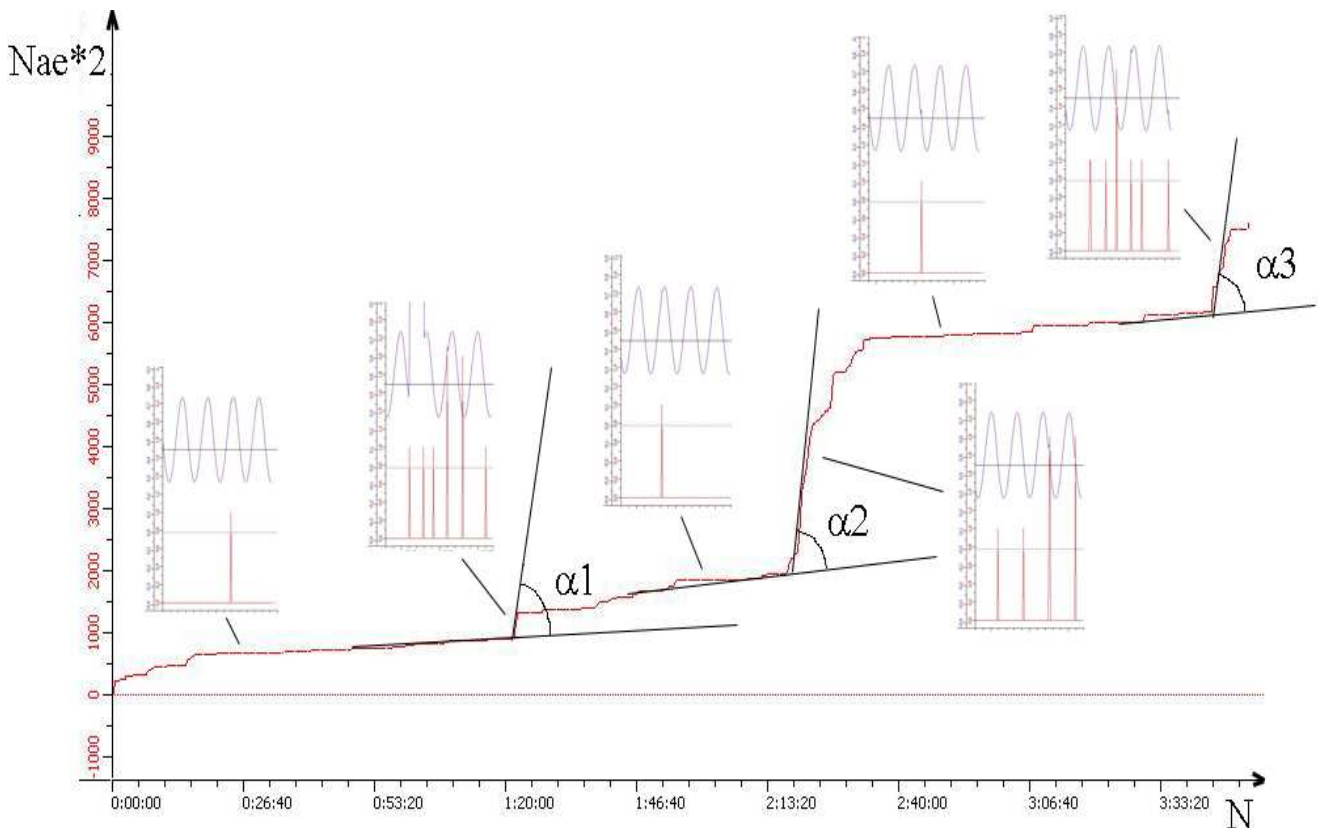


Fig.5 Specimens №1. Operating time – 415104 cycles. Summary AE signals Nae in versus number of loading cycles N (times). Fragments of synchronous record of AE signal intensity and the load applied

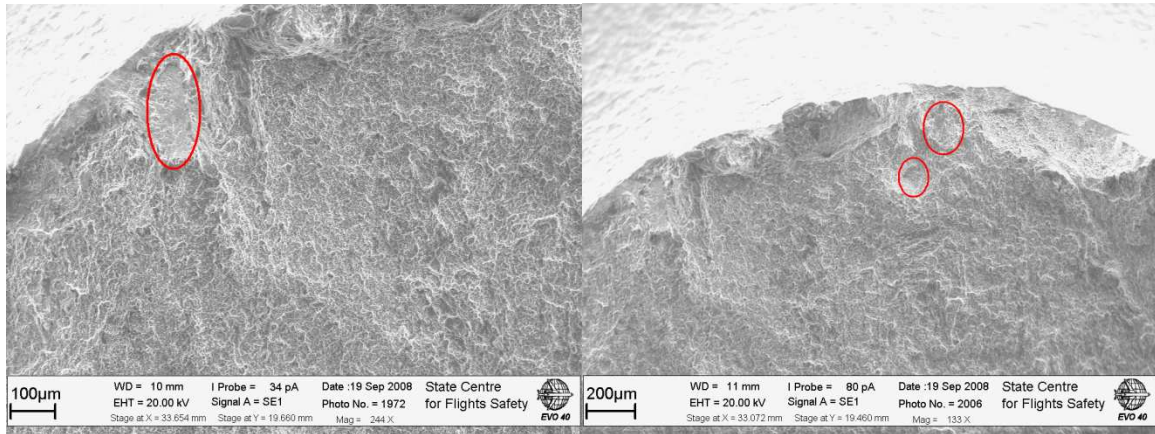


Fig.6 Specimens №1. Operating time – 415104 cycles. Fractographic investigation of the fracture.

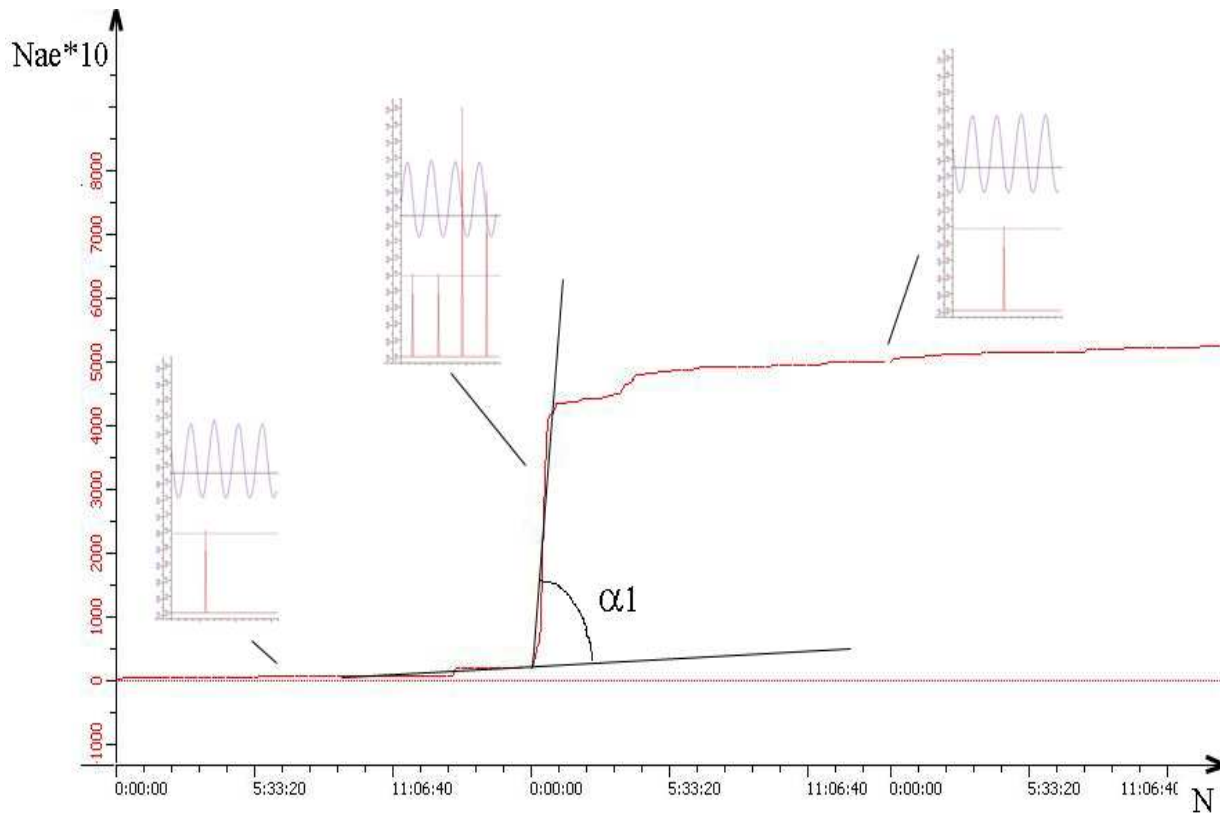


Fig.7 Specimens №2. Operating time – 4725809 cycles. Summary AE signals Nae in versus number of loading cycles N (times). Fragments of synchronous record of AE signal intensity and the load applied

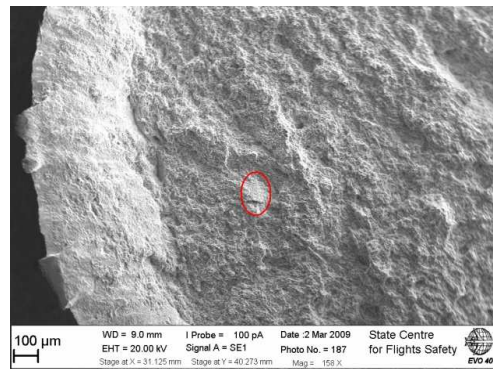


Fig.8 Specimens №2. Operating time – 4725809 cycles. Fractographic investigation of the fracture.

At the same time, on each sample near the surface or at a certain distance from the surface there were discovered some small areas of quasi-brittle destruction of the material. Just these areas of the fracture reflect the fact that in the material of the sample there has already arisen a zone of material having lost its strength (weakened), which was being registered by “ $\alpha$  - criterion” on the ground of the acceleration in the accumulation of summary AE signals. Thus the break on the dependence of total AE on loading cycle number (“ $\alpha$  - criterion”) is identified as the moment of the conception of a fatigue crack of microscopic size.

In some cases in the process of cyclic loading, on the dependence of summary acoustic emission on loading cycle number there may be observed a few breaks, a few  $\alpha$  angles (see Fig. 5). The results of fractographic investigation of the fractures of these samples showed that the number of  $\alpha$  angles corresponds to the number of fatigue microcracks arisen (see Fig.6).

### CONCLUSIONS

From the investigations conducted the following may be concluded:

- The first break on the dependence of summary AE on loading cycle number (“ $\alpha$ ” criterion) is identified as the moment of the conception of a fatigue crack of microscopic size.
- If at the initial testing stage on the dependence of summary AE on loading cycle number there are observed a few breaks, a few  $\alpha$  angles, the number of  $\alpha$  angles corresponds to the number of fatigue cracks formed.
- In the model of quantitative evaluation of fatigue crack growth speed by the summary AE in the loading cycle in crack conception stage it is necessary to take into consideration in the calculation only that summary AE in each loading cycle, which falls to the stage of summary AE accelerated growth on loading cycle number (« $\alpha$ » criterion)

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### Aleksejs Nasibullins, Aleksandrs Urbahs, Muharbijs Banovs. Nogurumu plaisas rašanās kontrole ar akustiskās emisijas metodi titānu paraugu izmēģinājumos

Tradicionālās nesagraujošās kontroles metodes, kuras tiek izmantotas konstrukcijas tehniskā stāvokļa noteikšanai izmēģinājumu laikā (vizuāli optiskās, ultraskaņas, virpuļstrāvas, magnētisko pulveru u.c.), ne vienmēr izrādās efektīvas. Sagrūšanas procesa kontroles uzticamības paaugstināšanai ir lietderīgi papildus pielietot akustiskās emisijas metodes, ar kuras palīdzību ir iespējams ne tikai konstatēt noguruma defektus sarežģītās konstrukcijās un savienojumos, bet arī sekot to attīstībai.

Tiek uzskatīts, ka akustiskās emisijas atkarības no sloģošanas ciklu skaita grafika pirmais lūzuma punkts ir viens no noguruma plaisas rašanās kritērijiem ( $\alpha$ -kritērijs), pielietojot AE metodes. Lai apstiprinātu šo faktu, tika veikti titāna sakausējuma BT3-1 paraugu ar stīpinātu virsmu sērijas noguruma izmēģinājumi. Izmēģinājumu paraugiem tika pielikta cikliska, nemainīgas zīmes slodze. Visu paraugu sloģošanas frekvence bija 30 Hz. Noguruma plaisu parādīšanās paraugos AE kontroles rezultāti tika attēloti kā summārās AE atkarības no sloģošanas ciklu skaita grafiki un AE signālu intensitātes un pieliktās slodzes sinhronā ieraksta fragmenti. Šo paraugu lūzumu fraktogrāfiskās izpētes rezultāti parādīja, ka pirmais summārās AE atkarības no sloģošanas ciklu skaita grafika lūzuma punkts ( $\alpha$ -kritērijs) tiek identificēts kā mikroskopiskas noguruma plaisas rašanās moments.

### Алексей Насибуллин, Александр Урбах, Мухарбий Банов. Контроль зарождения усталостной трещины методом акустической эмиссии при испытаниях титановых образцов

Традиционные методы неразрушающего контроля, которые используются для контроля за техническим состоянием конструкций в процессе испытаний (ультразвуковые, токовихревые, магнитопорошковые, рентгеноскопические и т.д.) не всегда оказываются эффективными. Для контроля за

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процессом разрушения полезно дополнительно использовать метод акустической эмиссии, с помощью которого можно не только констатировать появление дефектов в испытываемых конструкциях, но и следить за их развитием.

Считается что первый перелом на графике зависимости суммарной акустической эмиссии от числа циклов нагружения является одним из критериев ( $\alpha$ -критерий) возникновения усталостной трещины при использовании метода АЭ. Для подтверждения этого критерия были проведены усталостные испытания серии образцов из титанового сплава ВТЗ-1, упрочненных с поверхности. Все испытываемые образцы подвергали циклической знакопостоянной нагрузке с частотой 30 Гц.

Результаты испытаний представлены в виде графиков зависимости суммарной АЭ от числа циклов нагружения и фрагментов синхронной записи интенсивности сигналов АЭ и прикладываемой нагрузки. Проведено сопоставление данных полученных методом АЭ с результатами фрактографического анализа излома. Проведенные исследования показали, что первый перелом на зависимости суммарной АЭ от числа циклов нагружения ( $\alpha$ -критерий) является моментом возникновения усталостной трещины.