

Diagnostics of Fatigue Damage of Gas Turbine Engine Blades by Acoustic Emission Method

A.Urbach, M. Banov, V. Turko, Y.Feshchuk

Abstract—the work contains the results of complex investigation related to the evaluation of condition of working blades of gas turbine engines during fatigue tests by applying the acoustic emission method. It demonstrates the possibility of estimating the fatigue damage of blades in the process of factory tests. The acoustic emission criteria for detecting and testing the kinetics of fatigue crack distribution were detected. It also shows the high effectiveness of the method for non-destructive testing of condition of solid and cooled working blades for high-temperature gas turbine engines.

Keywords—acoustic emission, blades for gas turbine engines, fatigue damage, diagnostics

I. INTRODUCTION

THE modern stage of aviation equipment development is characterised by tougher operational requirements and increase of load-carrying capability of structural units. Ensuring operating safety of parts is related to the improvement of known non-destructive methods and tools for testing as well as to the development of new methods, which ensure higher level of reliability and accuracy of diagnostic check. The experience of using cooled and solid blades for gas turbine engines (GTE), which are used in complex conditions of randomly changing loads, shows that in most cases their failure is related to the appearance and development of fatigue cracks. For cooled blades, the area of cracks is usually located in internal cavities; while for solid blades, it is located within the subsurface layer of the material. Fatigue cracks appear under the influence of operational factors, i.e. the effect of considerable thermocyclic and mechanical loads.

Besides operational factors, fatigue strength of blades is influenced by properties of the material, manufacturing and assembly technology, geometry, presence of constructive stress concentrators, etc. In particular, formation of cracks in internal cavities of cooled working blades is related to presence of different stress concentrators, i.e. presence of canals and structural components of a complex shape that intensify the process of air cooling. In addition, as a result of interaction between cooling air and material heated to high temperatures, additional tensile stresses appear on the inner surface of blade body.

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Non-destructive testing of working blades by traditional methods is difficult to ensure for the following main reasons:

–lack of free access to the internal cavity of cooled blades with the aim to perform testing:

–complexity of blades construction:

– for solid blades, impossibility of revealing microscopic cracks hidden under the surface.

This problem was solved by using the acoustic emission (AE) method [1]. The AE method has considerable advantages over other non-destructive testing methods:

– high sensitivity (ability to reveal defects on a micro level);

– ability to detect growing defects only, which are the most dangerous for products;

– possibility of monitoring objects with fixed sensors regardless of defect location in product material (no need to scan), etc.

The AE method makes it possible to determine the moment of crack initiation with high accuracy and reliability and observe their growth in the process of fatigue loading of different products [2, 3].

II. METHOD OF EXPERIMENTAL INVESTIGATION

With the aim of assessing fatigue strength, an inspection lot of gas turbine engine blades was subjected to stationary fatigue tests in plant conditions until the first signs of destruction appeared. The decrease of natural-vibration frequency of a blade body by a specified value was considered to be such a sign. However, this criterion is true only when a fatigue crack has penetrated rather deeply. In addition to that, in a number of cases, nonmonotonic change of natural-vibration frequency is observed, which is conditioned by the process of damage accumulation influence and changes in the conditions of blade root nipping during blade body rigidity tests. The influence of the given factors leads to "blurred" interpretation of the basic stages of damage accumulation process in blades material. The application of the AE method provided the opportunity to considerably reduce the ambiguity.

The method was tried out in plant conditions on a shake table used for determining fatigue characteristics of working blades. In hard loading conditions, the blades were excited at resonance frequencies according to the first bending form of vibrations. The level of stresses σ acting in the most loaded section were determined from the vibration amplitude of a shroud, which is measured with the help of an optical device according to calibration curve "amplitude–stress" obtained on the basis of results of preliminary strain measurement. At the same time the error of stress measurement did not exceed 5%.

At the first stage of investigation, two lots of single-type

solid blades made of heat-resistant nickel base alloy were subjected to fatigue loading. The maximum cycle stress in dangerous section by the first bending form of vibrations for the first lot was 200 MPa, while for the second one it was 250 MPa.

At the second stage of investigation, cooled blades with different embodiment of internal cavities were subjected to fatigue loading. For the material of cooled blades, the maximum cycle stress in dangerous section during stationary cyclic loading exceeded 1.3 times the fatigue limit and was $\sigma = 220$ MPa.

Reception and processing of AE signals was performed with the help of АФ-20М device [4] in the frequency range of 420 to 480 kHz with coefficient of amplification equal to 85 dB. The selected operating mode of AE device provided good interference immunity during testing in plant conditions. Piezoelectric transducer with the resonance frequency of 450 kHz was fixed on the flat surface of the blade root. Transformer oil was used to achieve acoustic contact. For the first lot of blades, total AE N_{AE} and number of load cycles N were recorded with frequency meters of Ч3-33 type. At the same time graphical construction of dependencies $lgN_{AE} = f(lgN)$ was carried out. For the second lot, the recording of energy E of AE signals was additionally carried out with the help of H-327-1 recorder.

III. RESULTS OF EXPERIMENTAL INVESTIGATION

Fig. 1 presents the data characterizing dependencies $lgN_{AE} = f(lgN)$ at the example of six tests of the first lot of solid working blades. It is obvious that all dependencies have qualitatively similar nature: areas of slow growth of total AE are followed by areas of its sharp increase.

Intersection of the specified areas form angles α_{cr} (α -criterion) [5, 6] that characterize the presence of inflection point in the graph. Tests of the first lot of blades were stopped at the point when α_{cr} appeared. For the second lot, reaching maximum value E_{max} (energy criterion – E_{cr}) by AE energy E was considered the criterion for stopping the tests.

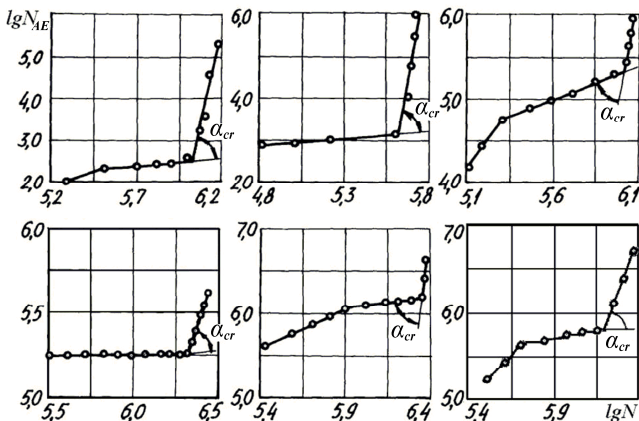


Fig. 1 Change of total AE during cyclic loading of solid blades with the use of α -criterion

Acoustograms of energies and graphs of dependencies $lgN_{AE} = f(lgN)$ for tests of five solid blades from the second lot are shown in Fig. 2 and 3.

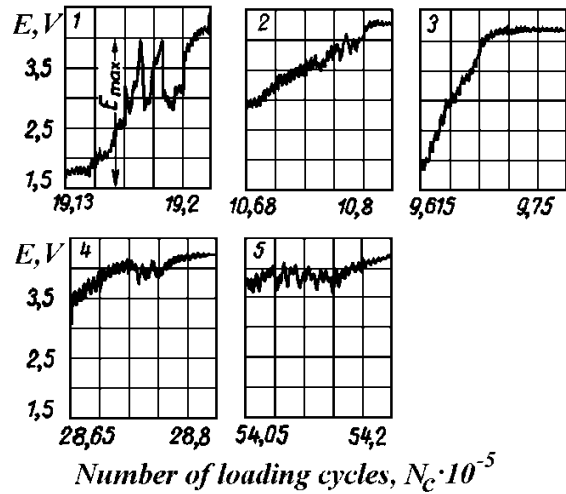


Fig. 2 Acoustograms of AE energy change during cyclic loading of solid blades with the use of E-criterion

In spite of different testing conditions from the point of view of stresses in the dangerous section of the body of the first and second lot of working blades, the behaviour of dependencies $lgN_{AE} = f(lgN)$ with the use of both α -criterion and E-criterion was identical (see Fig. 1, 3). The difference between graphs lies in the fact that testing of the first lot was stopped with the first appearance of α_{cr} (see Fig. 1), while the use of E_{cr} for the cessation of tests is followed by the appearance of one or more α_{cr} (see Fig. 3). Thus the graphs obtained for blades 2 and 3 have one α_{cr} ; the ones obtained for blades 1 and 4 have two α_{cr} ; the ones obtained for blade 5 have four α_{cr} .

However, the results of subsequent luminescent control revealed the presence of fatigue cracks in each of the both tested lots of working blades. The number of α_{cr} formed in the process of using E-criterion usually corresponds to the number of fatigue cracks that appeared during the tests.

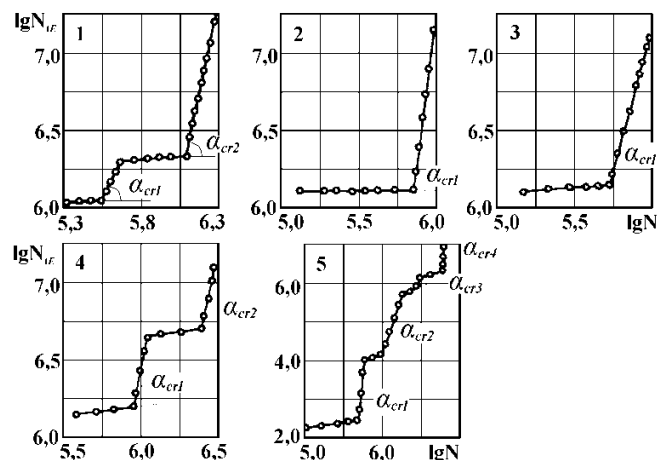


Fig. 3 Change of total AE during cycling loading of solid blades with the use of E-criterion

Using the above mentioned criteria, fatigue cracks were registered not only along the blade body but also in the root, i.e. in the place of nipping on the shake table. The comparative evaluation of blade fatigue cracks by length parameter, which was carried out with the help of luminescent control, showed that the length of cracks revealed on the basis of E_{cr} in all cases exceeded the size of cracks detected on the basis of α_{cr} . Thus it can be presumed that the appearance of an initial crack in a working blade during testing occurs long before reaching the specified threshold E_{max} (E_{cr}). Thus in Fig. 3, the first appearances of α_{cr} characterize the formation of initial cracks. However, the blade still does not lose its rigidity properties (natural-vibration frequency of a blade body measured using manufacturing technology still does not decrease) right till the end of the test. Therefore, the criterion assesses the real operability (survivability) of those blades that already have initial cracks. The quantitative estimation of this value showed that blades with cracks detected in accordance with the first α_{cr} do not lose their operability (by the criterion of natural-vibration frequency) in the range of 30 to 90% of the total loading time. One of the possible criteria for early detection of fatigue cracks in the process of fatigue loading is the second derivative $(\lg N_{AE})''$ by time from function $\lg N_{AE} = f(\lg N)$. Fig. 4 presents an example of change of the first $(\lg N_{AE})'$ and second $(\lg N_{AE})''$ derivatives on the basis of results of testing the third blade from the first lot (see Fig. 1). The behaviour analysis of derivatives in the process of cyclic loading shows that the stage of loading at which the second derivative becomes positive (see Fig. 4 point 2) corresponds to the moment of fatigue crack initiation.

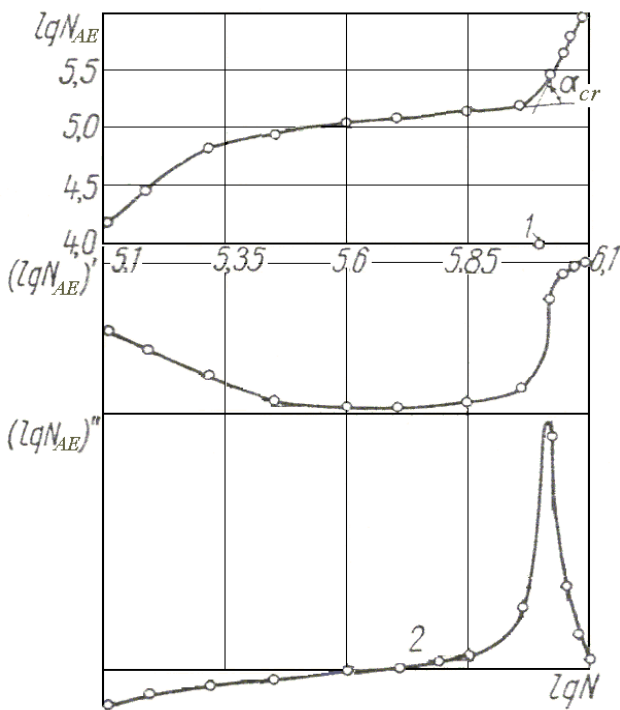


Fig. 4 The changes in time of the first and second derivatives of functions $\lg N_{AE} = f(\lg N)$: 1 — moment of crack detection by α -criterion; 2 — moment of crack detection by $(\lg N_{AE})'' > 0$

Thus, to detect the moment of fatigue crack initiation during a fatigue test, which separates the first stage of fatigue accumulation of damage from the second one, α -criterion, E-criterion as well as the value of the second derivative when it takes on a positive value can be used. The latter criterion ensures earlier detection of a crack; then, from the point of view of accuracy, there follows α -criterion; and E-criterion is the “roughest” criterion for detection of longer fatigue cracks. α -criterion appeared to be the easiest-to-operate criterion for detection of the moment of fatigue crack initiation. The correctness of the given criterion choice as well as its reliability were checked on both solid working blades of other construction and cooled working blades of other construction.

For cooled blades, investigation was carried out in three stages. At first, in the conditions of stationary cyclic loading with the stresses of $\sigma = 220$ MPa, the tests were carried out until the operation of the “roughest” criterion E_{cr} . In this case, the nature of dependencies $\lg N_{AE} = f(\lg N)$ is identical to the one that was obtained earlier for solid blades: areas of slow growth N_{AE} are followed by areas of sharp increase. Intersection of the specified areas form angles α_{cr} , similarly to the case with solid blades. At the same time none of the tested blades lost its rigidity properties (natural-vibration frequency of blade body remained constant). Fig. 5 presents the results of specified dependencies change at the example of one of the tested blades.

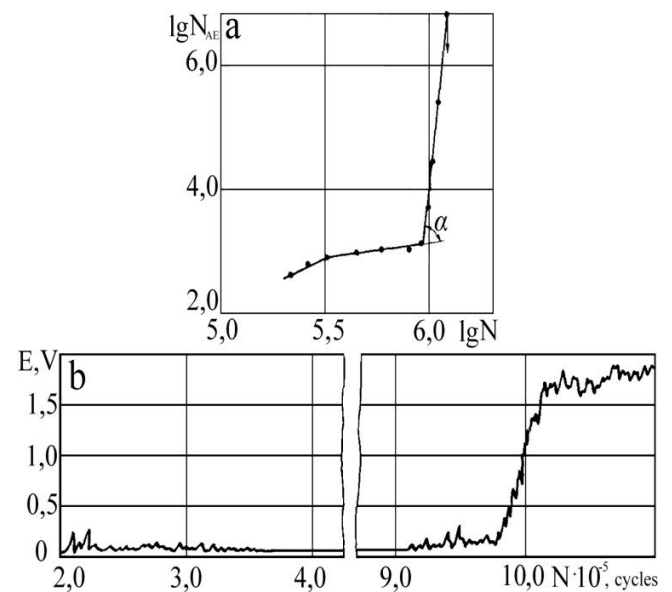


Fig. 5 The change of total (a) and energy (b) of AE signals in the process of cyclic loading of a cooled working blade (the point at which the tests were stopped is shown with an arrow)

Subsequently all blades were subjected to tests to reveal the presence of cracks with the help of traditional methods. The carried out luminescent control did not show any defects on the outer surfaces of the blades. After opening, defects of crack type were detected in the blades. Fig. 6a presents an example of a photo of inner cavity of one of the cooled blades

after its opening. It is seen that the fatigue crack in the blade, for which the dependency was obtained and which is presented in Fig. 5, appeared near the base of the cooling intensifier of a cylindrical shape (shown with an arrow). Fig. 6b presents a photo of fracture area along the crack. It is seen that the fatigue crack in this blade has developed to the depth, which is greater than half the thickness of the wall of blade body back, however it has not reached the outside surface yet. The metallographic analysis of other fractures along such cracks showed that they also had fatigue nature and were developing from the inner surface of hollow blades to their outside surface.

Thus the high efficiency of α_{cr} operation is demonstrated, while the use of E_{cr} in these tests gave the opportunity to reliably register the appearance of fatigue cracks by using traditional methods. Further metallographic investigation demonstrated that the earlier the tests were stopped after α_{cr} registration the smaller was the crack. In cases when tests were stopped practically right after the registration of angle α , cracks could be detected only after long-term exposure (more than three days) with the help of the luminescent method. Subsequent metallographic analysis of sections of these areas confirmed the presence of fatigue cracks (Fig. 6c).

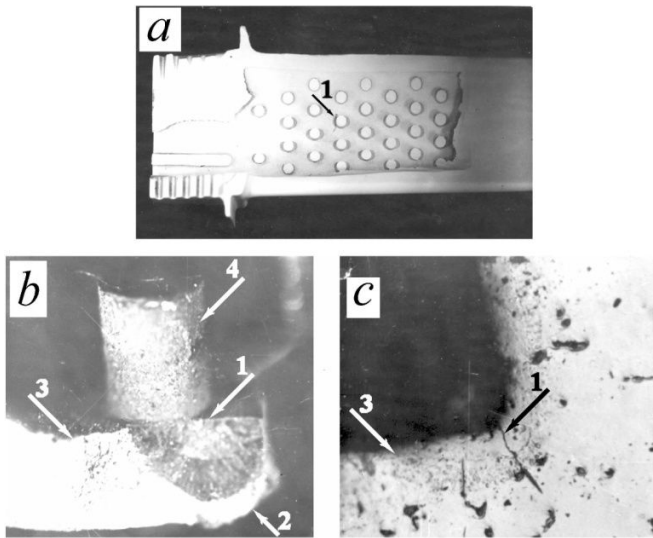


Fig. 6 Photo of a blade with a crack: a) – general view of the internal cavity after opening, b) – area of fracture along the crack (x10), c) – metallographic section (X100): 1 - crack, 2 – outside surface of blade, 3 – inner surface of blade, 4 – cooling intensifier

Further approbation of the obtained criteria was carried out with the aim of studying the possibility of monitoring cracks in internal cavities of cooled blades by the AE method under stresses that do not exceed operating stresses ($\sigma=50$ MPa). It is possible to achieve the set objective if there are blades with fatigue cracks in the internal cavity of the body, which appeared during operation. As far as at present the defects of this type are not detected, the necessity of “growing” them on

purpose arose. The process of “growing” in certain moments involved the repeated use of fatigue tests of α_{cr} and E_{cr} , the essence of which lies in the following facts: The investigated blade was preliminarily subjected to cyclic loading that created the stress equal to 50 MPa. If AE was not recorded, the blade was considered defect-free. Then, in order to accelerate the experiment, the stress was increased up to 220 MPa with subsequent stepwise decrease at the moments of time corresponding to the initial appearance of a crack and then corresponding to its accelerated growth with new stress values. Graphical construction of dependency $\lg N_{AE} = f(\lg N)$ was carried out right in the process of testing using the above described method. The load was reduced at the moments of time that corresponded to reaching AE signals energy value E_{cri} after the recording of angles α_{cri} (Fig. 7) where $i = 1, 2, 3, \dots$ is a number of stepwise reductions of load.

The external load at the stage of reduction was chosen with the aim of maintaining the growth of the appeared crack monitored taking into consideration the total AE change, which is reflected on the frequency meter. The loading was reduced until continuous counting N_{AE} occurring in three or four digits and indicating at the accelerated growth of the crack decreased to the count in the first digit when the growth of the crack slowed down considerably. When the count stopped, the growth of the crack was considered to stop as well.

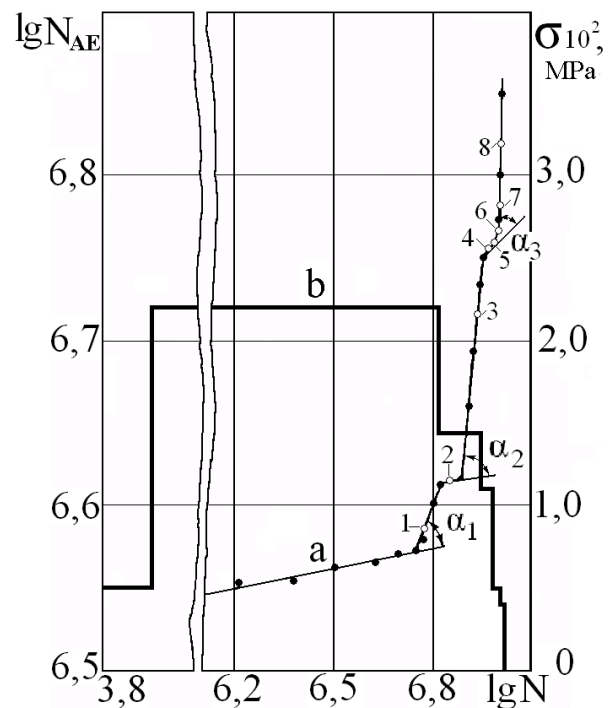


Fig. 7 The change of total AE (a) in case of staged step change of stress (b) in the process of cyclic loading:

- – experimental points; o – points corresponding to the record of acoustograms of AE signals energy change

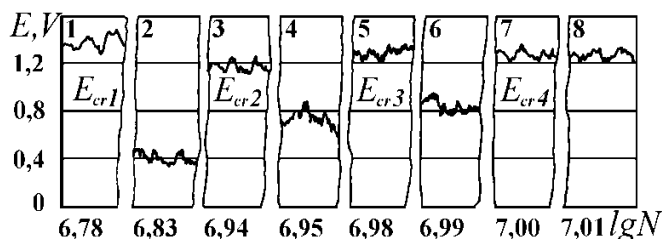


Fig. 8 Acoustograms of AE signals energy change at typical stages of loading of a cooled blade

Thus the first reduction was made after operating time $lgN = 6.81$ (see Fig. 7b) after the formation of angle α_{cr1} and subsequent operation of energy criterion E_{cr1} , which characterized the reliable appearance of fatigue crack. The change of AE signals energy in the area prior to the reduction of stress is presented in Fig. 8 (acoustogram area 1, obtained in point 1) with $lgN = 6.78$ (see Fig. 7a). With a new stress value which is equal to 145 MPa (see Fig. 7b) the deceleration of the crack occurs, which is confirmed by the change of total AE (see Fig. 7a) and the reduction of energy level (see Fig. 8, acoustogram area 2) obtained in point 2 with $lgN = 6.83$ (see Fig. 7a). In the process of subsequent cyclic loading, the growth of the crack accelerates (angle α_{cr2} is formed). The level of energy increases again up to value E_{cr2} , which can be well seen in Fig. 8 (acoustogram area 3 obtained in point 3) with $lgN = 6.94$ (see Fig. 7a). Then, with $lgN = 6.95$, the following reduction of stress up to 110 MPa was made (see Fig. 7b), which entailed the deceleration of the crack and, correspondingly, the reduction of values of AE parameters (see Fig. 8, acoustogram area 4). After the recording of angle α_{cr3} , the level of energy increases up to value E_{cr3} (see Fig. 8, area of acoustogram obtained in point 5). At the moment corresponding to operating time $lgN = 6.99$ the stress was reduced up to 50 MPa (see Fig. 7b). The growth of the crack decelerated for a short time, which is insufficiently reflected in Fig. 7a and well illustrated in Fig. 8 (area 6 of acoustogram obtained in point 6), with $lgN = 6.99$ (see Fig. 7a). Then the growth of the crack accelerates again, which is confirmed by the increase of AE energy level up to another energy criterion E_{cr4} (see Fig. 8, acoustogram in point 7). The next reduction of stress up to 40 MPa practically does not exert any influence on the velocity of crack growth; energy criterion remained at the same level of E_{cr4} (see Fig. 8, acoustogram in point 8). When the stress was below 40 MPa, counting with the help of the frequency meter stopped. During the subsequent luminescent control of blades tested with the help of the above described programme no cracks were detected on the outer surface. However, after the opening of blades, both the luminescent control and the metallographic analysis confirmed the presence of cracks of fatigue nature on inner surfaces.

Fig. 9 presents a photo and a diagram of blade fracture along the crack (shown with arrows), for which the dependencies presented in Fig. 7 and 8 were obtained. It is seen that the crack in this blade has reached approximately half the thickness of the wall and has not reached the outer surface.

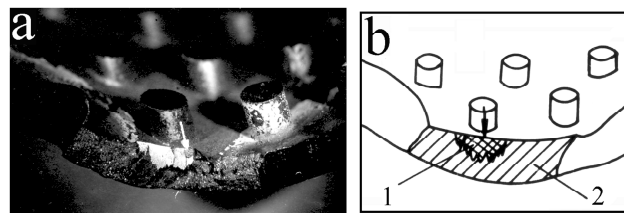


Fig. 9 Photo and diagram of blade fracture along the crack

Thus the results of tests of cooled working blades for GTE related to the “growing” of operational cracks on inner surfaces by using such AE criteria as α_{cr} and E_{cr} confirmed the effectiveness, reliability and accuracy of these tests and subsequently were used for the testing of operating blades [4].

IV. CONCLUSION

On the basis of a series of researches in the process of factory tests, the work demonstrates the possibility of assessing fatigue damage of blades by using the acoustic emission method. The acoustic emission criteria for detecting and testing the kinetics of fatigue crack distribution were detected. It is shown that the appearance of fatigue cracks can be reliably recorded at the early stage with the help of criteria of acoustic emission testing: α -criterion, E-criterion, as well as the value of the second derivative lgN_{AE} . In practice, the simplest and most reliable criterion for detecting the moment of fatigue crack formation is α -criterion. The work confirms high efficiency of the method for non-destructive testing of the condition of solid and cooled working blades intended for high-temperature gas turbine engines.

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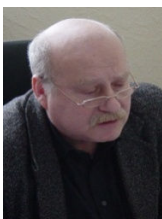
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