PREVENTION OF LOW CYCLE FATIGUE FRACTURE OF AVIATION ENGINE CRITICAL PARTS

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Abstract

Certification requirements to gas turbine engine disks, design and production process solutions ensuring enhancement of disks strength reliability and life and decrease in disk mass, methods for validation of compliance of disks with certification requirements are discussed.

Method of safe inspections intervals evaluation is developed. The method is based on microfractographic reconstitution (using the results of electron microscopic analysis of a fracture surface microrelief) and calculated prediction of fatigue cracks kinetics under simple and complex loading cycles typical for civil and military aero engines.

1 Introduction

Disks (blisks, rotor spacers) refer to main (critical by fracture effects) parts of aircraft gas-turbine propulsive engines. Moreover, mass of these parts largely defines mass and specific weight of engine as a whole.

In this connection, in the process of engine development, manufacture, certification and operation, particular attention is given to optimal design and strength reliability of these parts.

The points discussed below include certification requirements to disks, design and production process solutions ensuring enhancement of disks strength reliability and life and decrease in disk mass, methods for validation of compliance of disks with certification requirements.

Since disks of propulsive engines refer to main engine parts. Disk fracture in service must be an extremely improbable event to be validated during engine certification.

2 Provision of disks strength reliability

For reasons of low mass, disks are manufactured from high-strength titanium alloys, steels and nickel-base alloys (powder or deformable). Arrangement of disk alloys qualification is of major importance. The results of structural strength investigations of specimens cut out from disk workpieces (forgings) should be used both for validation of parts strength and life during engine certification and development of technical conditions for delivery of workpieces in such a way as to exclude possibility of manufacturing disks from material featuring unsatisfactory properties. Disks strength reliability is assessed as a rule (except for crack resistance characteristics) with the use of material properties at $\bar{A}$-3δ_A level, where $\bar{A}$ is average characteristic value, δ_A is root mean square deviation. In the process of manufacture it is advisable to perform rejection based on $\bar{A}$-2δ_A material strength characteristic level.

Optimization methods based on multicriterion approaches with 3D calculations and with due regard for actual service conditions throughout the whole flight cycle including determination of stress-strain state of parts at unsteady regimes are effectively usable to ensure strength reliability of disks with minimization of their masses.

To decrease disk contour load, it makes sense to apply lightweight blades (especially for fans where hollow metallic and carbon plastic blades are used and for low pressure (LP) turbines where blades from lightweight monocrystal alloys and titanium γ-aluminide are used) and optimize quantity of blades. It is advisable to manufacture path platforms of fan wheels from lightweight materials and separately from blades.

A drop in temperature gradient on disk radius would be appropriate for lowering temperature stresses level in disks of turbines and last high pressure compressor (HPC) stages.

Disks must feature sufficient load-carrying capability both in normal operation and when defects occur. Shaft fracture, automatic control system failure and some other defects can cause an increase in rotor speed under service conditions. Provision of disks load-carrying capability for intermediate pressure (IP) and LP turbines and power (free) turbines is the most intricate problem. A rational selection of approach used to prevent inadmissible turbine rotor overspeeding (to limit maximum possible rotor speed) in cases of shaft fracture, shifting and disconnecting is of great importance. For these purposes, use can be made of ranking of strength margins in a “disk-blades” system (fracturing of blades in root section at rotor overspeeding conditions excluding disk fracturing), fitting of turbine rotor on stator along periphery blade sections in case of turbine rotor axial shifting after shaft fracturing (cutting-off of mass fracture of blades through an appropriate selection of axial clearances between rotor and stator), cutting out of blade airfoils with the use of special devices, mechanical and electronic systems for fuel shuttingoff or compressor surge initiation at shaft fracturing. During certification it is required to validate sufficient load-carrying disk capability for the most unfavorable combination of material properties. Disk load-carrying capability therewith depends on disk material strength and plasticity characteristics. If appropriate experimental data required for assessment of disk load-carrying capability are available, empirical coefficients may be used. Nowadays this task is solved by calculations. Experimental verification of different criteria for attainment of loss of load-carrying capability of complex-shaped disks has been carried out at CIAM [1, 2]. In particular, it was shown that prediction results for fracture frequency of disk investigated by energy and strain criteria well agree with experimental results.

When investigating load-carrying capability of welded rotors, it is essential to allow for mutual supports of all of disks comprising this rotor. Survivability of welded rotor exceeds survivability of its components [1, 2].

To prevent inadmissible disk growth or embrittlement of its material in service, there is a need, on the one hand, to optimize disk thermal and stress-strain state, and on the other hand, to manufacture disk from alloy having appropriate characteristics, that is, not susceptible to embrittlement in service. Auto-overspeeding of rotor up to onset of plastic stresses in it is also performed with this purpose. Disks must be designed to provide admissible (with regard to high static loading) disk vibration stresses levels. Among disk life values determined with corresponding margins – before low cycle fatigue (LCF) crack initiation (with regard for initial defects) and with regard for safe crack propagation from initial defects, the lesser one should be allowable for service.

Life of rotor disk before LCF crack initiation should be validated either by equivalent-cyclic tests (within engine or in spin pit) or by 3D disk calculations performed for unsteady operation and data on LCF material resistance. In doing so, it is important to take into account possible effect of dwell under loading on LCF resistance. There is a need also to verify technique for life validation using data on LCF material resistance (especially, technique for selection of required cyclic durability margin). To provide high disk durability before LCF crack initiation, it is necessary not to use intensive stress concentrators in construction. In particular, it is necessary not to use holes in disk (for bolt connections, equalization of pressure in cavities, supply of cooling air to turbine blades, etc.), to limit minimum values of fillet radii, not to use multitooth fir-tree roots.

Enhancement of cyclic durability is aided by many things, among them use of circular (nonlinear) roots in fans, use of low-tooth fir-tree roots, use of off-centre holes, optimization of these holes forms. Decrease in stress concentration is effective to increase durability of serial disks. Use of spline cutting out in high nominal loadings area, rebroaching of root slots with removal of damaged material layer and/or increase in radius of bottom-bolt slot matching have found application. If need be to use stress concentrators, they must be located in low nominal stresses areas. A number of stress concentrators (for example bolt holes), a form and dimensions of stress concentrator features should be optimized. Materials used should feature high LCF resistance. Application of gradient materials is possible in sight. There is a wide use of surface hardening methods; auto-overspeeding of rotor up to onset of plastic stresses in it is applied also.

To ensure high disk durability with consideration for possible initial defects it is necessary to minimize sizes and quantity of metallurgical defects. This is provided, specifically, due to increase in alloy purity during ingot melting.

While applying powder metallurgy methods, initiation of defects (carbides, oxides) along boundaries of primary grains must be excluded technologically. To decrease ceramic inclusions sizes and quantity, there is a need to realize a set of special actions, among them restriction of maximum size of granules used. It is not recommended to use welding for rotor manufacture, except for friction welding (inertial or linear), and especially casting (even when hot isostatic pressing is applied in order to decrease internal porosity. It is essential to use highly sensitive non-destructive inspection (NDI) methods with probabilistic assessment of defects detectability performed by NDI methods used. It is important that disks should be manufactured from high crack resistance alloys.

High durability and survivability in the process of crack propagation (fail-safe property) are inherent to multi-web disks, welded contractions, constructions containing special crack stoppers.

At service conditions it is necessary to check accumulated damage and to determine residual disks durability. Scheduling of maintenance is of great importance, especially this concerns disks NDI during engine repair.

Below is a more detailed consideration of physical-mechanical aspects of stable growth of LCF cracks in gas-turbine engine disks. Simulation of stable growth of fatigue cracks is required to define disk residual durability and inspection periodicity in service.

3 Estimation of disk residual durability and inspection periodicity in service

Stable growth of fatigue cracks corresponds to the second stage of kinetic diagram «fatigue crack growth rate V – stress intensity factor (SIF) range ΔK» and to formation of measurable fracture surface microrelief (fractorelief) i.e. fatigue striations. Period of stable crack growth comprises a considerable part of total cyclic durability of high-stress constructions susceptible to LCF (such as, disks of aircraft gas-turbine engines). Reliable determination of period of stable LCF cracks growth makes it possible to ensure fail-free operation of such constructions due to assignment of safe intervals for crack inspection during which possible cracks have no time to go beyond stable growth between inspections. In addition to solution of practical tasks, investigation of stable fatigue crack growth is of fundamental importance because of universality of its behavior, as well as presence of natural measure for stable crack growth rate (striations spacing) enabling theoretical models to be verified.

Modeling of stable fatigue crack growth is based in this paper on consideration of fracture mechanism acting at front of fatigue crack during its stable growth stage. This mechanism determines both fatigue crack kinetics and fractorelief. An understanding of this mechanism is needed for creation of mathematical model of fatigue growth and determination of relation between crack kinetics and fatigue striations spacing S which makes it possible to verify the model on the basis of fractographic analysis and to study the regularities of fatigue growth in full-scale conditions.

Unlike traditional approaches of fracture mechanics which are based on simulation of material in the form of homogeneous continuum and explain dependence between crack growth rate V and linear-elastic parameter ΔK by negligibly small effect of plastic deformation on crack kinetics, the model developed is based on notion of critical (prior to fracture) fragmented structure formed at a crack front as a result of intensive repeated plastic deformation located here and also on notion of high-energy-type fracture mechanism of periodic splitting-rupture (MPSR) determined by this structure [3]. Critical fragmented structure has two layers (micro- and mesoscopic). Its large-scale elements (high-angle misorientation mesoboundaries of deformation nature) are located along main strain axes and represent internal stress concentrators [4]. Action of MPSR that is similar to splitting mechanism for static loading [4] and Gordon-Cook mechanism for anisotropic materials [5] may be schematized as follows (fig.1):

- As a result of brittle transversal splitting along mesofragments boundary the T – shaped crack tip is formed and fatigue striations (splits) are generated on both fracture surfaces. Maximum of external applied stress $\sigma^{ext}_{x\max}$, acting in a plane of a crack that perpendicular to crack front, is reached at some distance λ from crack front. As load increases in loading cycle, σ^{ext}_{x} stress is added to internal σ^{int}_{x} stress that is generated during plastic deformation in previous cycles and localized near mesofragments boundaries. When this sum reaches σ_{th} theoretical strength, a new brittle splitting appears along boundary at a distance $\approx\lambda$ from crack front (primary fracture).
- Subsequent rupture of ligament between split and crack front (secondary fracture) leads to: **1)** crack extension on $\approx\lambda$, **2)** formation of new front with T-shaped crack tip, **3)** creation of new fatigue striations separated from previous ones by broken ligament (see SEM image in fig. 1). During secondary fracture, splitting may occur along mesofragments boundaries inside ligament resulting in generation of secondary striations.
- Consecutive processes of splitting before crack front and fracture of ligament between splitting and front are repeated in every loading cycle, with the result that T-shaped crack tip is reproduced in every cycle and average distance between adjacent primary fatigue striations (striations spacing) $S\approx\lambda$ is equal to average crack length increment during a loading cycle, i.e. $S(l)=dl/dN$, where N is a number of cycles, l is a crack length (depth).

The model discussed above enables basic regularities of stable fatigue cracks growth to be explained. High-energy-type fracture process at stable crack growth stage arises from crack

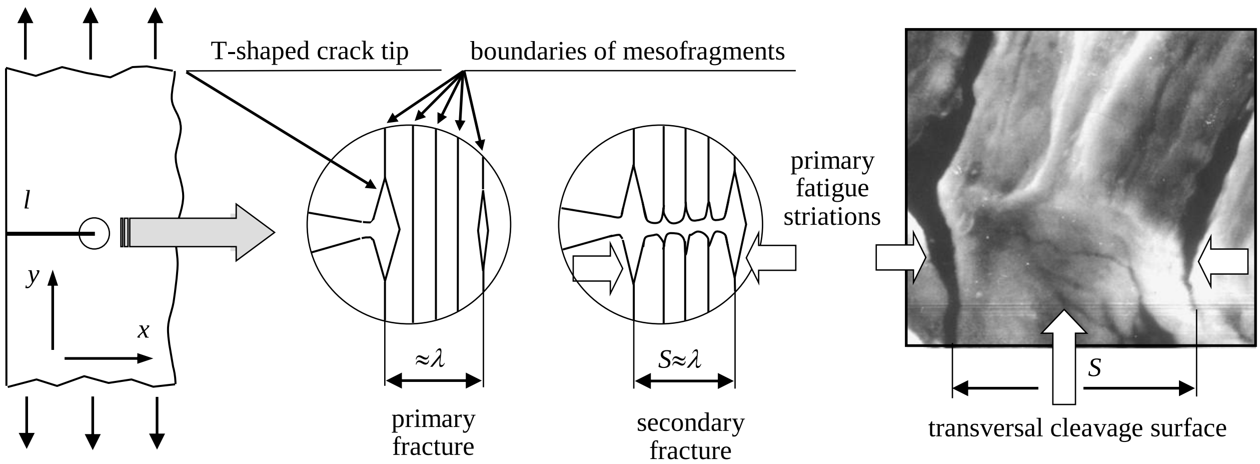

Fig. 1. Schematic Representation of MPSR Action (Cross-Section of a Crack Front) and SEM Image of Ttransversely Cleaved Striation.

"sticking" in transversal splits along mesofragments boundaries. These latter create fracture origins independent of initial (metallurgical) structure resulting in a weak dependence of stable crack growth on initial structure features, that is, relation of MPSR with self-organizing universal critical fragmented structure leads to decrease of its sensitivity to different initial structures. Orientation of plane of fatigue crack propagation at stable growth stage along normal to direction of maximum principal strain arises from development of primary brittle splitting along this direction, thus ligament rupture forms fracture surface in perpendicular direction (fig.1).

Independence of MPSR from various structures, its relation with universal limiting fragmented deformation structure (strength of materials with such structure approaches theoretical one [6]) and brittle nature of primary fracture (that is, keeping of linearly elastic material properties up to beginning of this fracture) enable material to be simulated in form of homogeneous linear-plastic medium having theoretical strength, when determining S value. Relation between S and ΔK is provided by mathematical invariant: value $\sigma_{x\max}^{ext}$ and location λ of maximum of stress σ_x^{ext} in linearly elastic body in front of a crack with T-shaped tip (in plane of main crack) at $l>>L$ depend only slightly on body and crack configurations as well as on type of tensile load [7, 8] (fig. 2):

$$\sigma_{x\max}^{ext} = (0.26 \div 0.29)\, K / \sqrt{L}\,, \quad \lambda = (1 \div 1.2)L \tag{1}$$

where L is length of symmetric split in crack tip, K is SIF for ideal (without such split) crack of l length. As follows from (1)

$$K \approx 3.5\sigma_{x\max}^{ext}\sqrt{\lambda}\,, \tag{2}$$

that is, for cracks of different configurations with different loads, SIF characterizes magnitude and location of maximum of stress acting in linear-elastic body in front of crack with T-shaped tip in plane of main crack provided that split length in crack tip is much

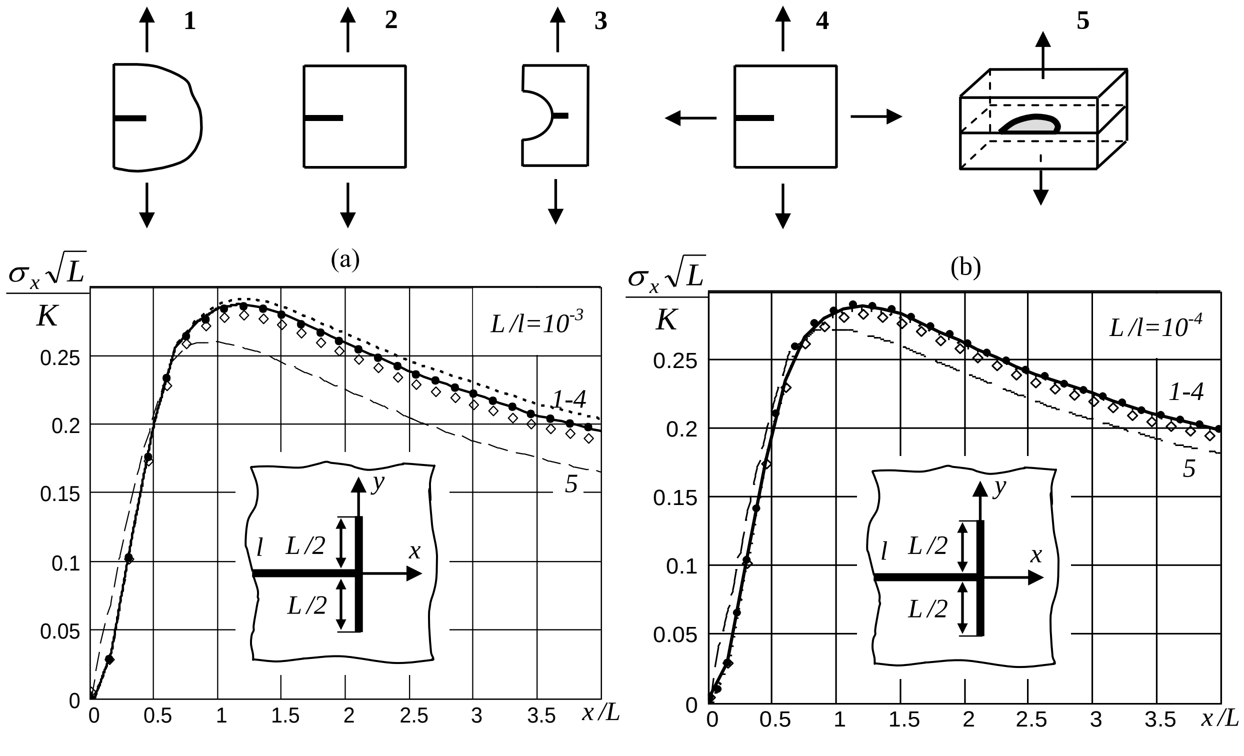

Fig. 2. Asymptotic Distributions of σ_x Normalized Stress in Front of a Crack with T-shaped Tip in $y=0$ Plane in Linearly Elastic Body with Different Body and Crack Configurations and Different Loads (Finite Element Modeling, Semicircular Crack (Model Number 5) Computations were Performed in Maximum Depth Point): a – $L/l = 10^{-3}$, b – $L/l = 10^{-4}$

less than crack length.

Since primary fracture is taken to be brittle, the applied σ_x^{ext} and internal σ_x^{int} stresses are additive with increasing load in loading cycle to the moment of originating fracture under condition

$$\sigma_x^{ext} + \sigma_x^{\text{int}} = \sigma_{th}. \qquad (3)$$

If load increases quasistatically (as typical for LCF cracks) and fracture occurs in $y=0$ plane at σ_x^{ext} stress maximum site, then, considering $S/l \approx 10^{-4} \div 10^{-3}$ from (1) and (3) with $S=\lambda$ and $\sigma_{th} = 0.1E$ (E is Young's modulus), we obtain

$$S = B(\alpha / \beta)^2 (\Delta K / E)^2, \qquad (4)$$

where $\alpha = K_* / \Delta K$, $\beta = 1 - \sigma_x^{int} / \sigma_{th}$, K_* is SIF value at the moment of primary fracture origination, $B=7 \div 10$ (with an accuracy of integer values).

Determination of a/β magnitude and m value of exponential dependence between ΔK and S in relation (4) is performed experimentally in the following way: S is measured and ΔK is calculated in several points along crack propagation route, then, linear regression ΔK dependence of S is plotted in dual logarithmic coordinates and its coefficients are calculated. Such investigations for LCF cracks in compressor and turbine disks (made from titanium and nickel based high temperature alloys) showed that $a/\beta \approx 1$ and $m=2$ [7]. Thus, when predicting stable growth of LCF cracks, universal kinetic equation

$$S = 10\,(\Delta K / E)^2 \qquad (5)$$

can be used (to provide conservative assessment of stable crack growth period, value of B coefficient in kinetic equation (4) should be taken equal to upper limit of its change range). Formula (5) includes SIF, strength characteristic of interatomic links $\sigma_{th} = 0.1E$ and mesoscale parameter S, relating magnitudes of different nature (mathematical ΔK and physical S and E) by simple relation and combining processes going on in macro-, meso- and microscopic scales.

Since $S(l)=dl/dN$, experimental dependence of stable crack growth period on crack length (depth):

$$N_1(l) = \int_{l_0}^{l} \frac{dl}{S(l)}, \qquad (6)$$

(where l_0 is initial crack length (depth)) and calculative dependence in view of crack growth law (5):

$$N_2(l) = \frac{E^2}{10} \int_{l_0}^{l} \frac{dl}{[\Delta K(l)]^2}. \qquad (7)$$

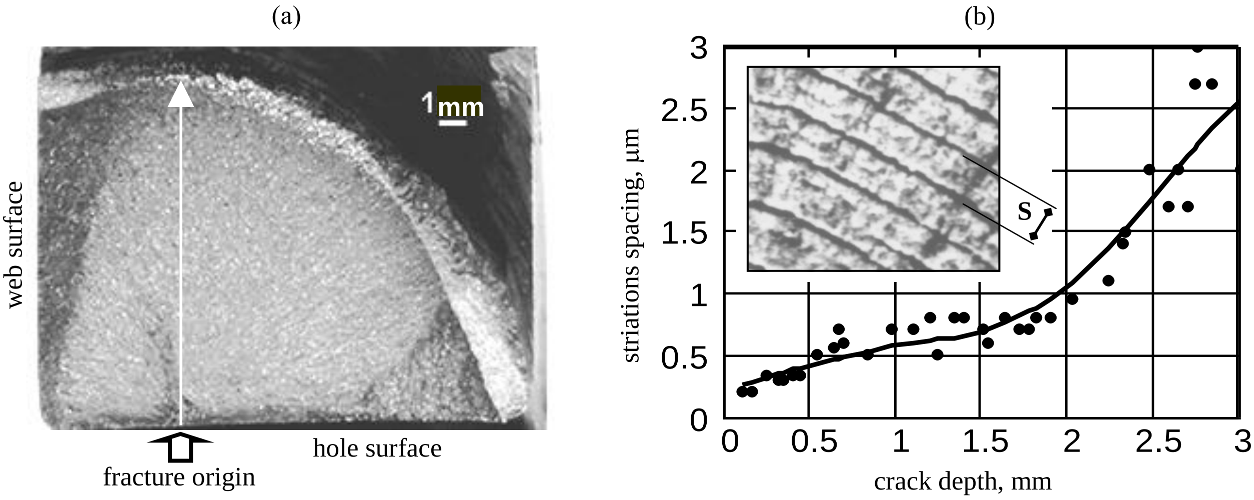

Fig. 3. Fractographic Reconstruction of Stable Fatigue Crack Growth in the Turbine Disk:
a) – Fatigue Fracture Surface (Arrow Indicates Direction of Striations Spacing Measurements);
b) – $S(l)$ Dependence (Experimental Points and Regression Curve) and Fatigue Striations

Figures 3, 4 and 5 illustrate results of calculation by formula (7) of LCF crack stable growth in aircraft engine turbine disk and verification of the calculation with use of relation (6). Investigation involves following steps:

- Microfractographic analysis of kinetics of two cracks of the same type in two identical disks (tested in similar conditions) with the aim to determine the *S*(*l*) dependencies and to define the cracks configuration evolution. Fracture surface for one of these cracks and corresponding *S*(*l*) dependence are shown in fig.3. As can be seen, the crack was originated in disk web on bolt hole surface near web surface and converted from surface crack into angular one. Stable crack growth occurred up to crack depth 3mm, its period constituted about *70*% of disk life and about *80*% of general crack growth period.
- Finite element modeling of stress state for the disk having cracks of depth *0.5*, *1*, *3*, *6*, *9* and *12.4*mm (crack configuration was established on the basis of fractographic studies), SIF calculation (in points of intersection of crack front with direction of striations spacing measurements, see fig.3a) and

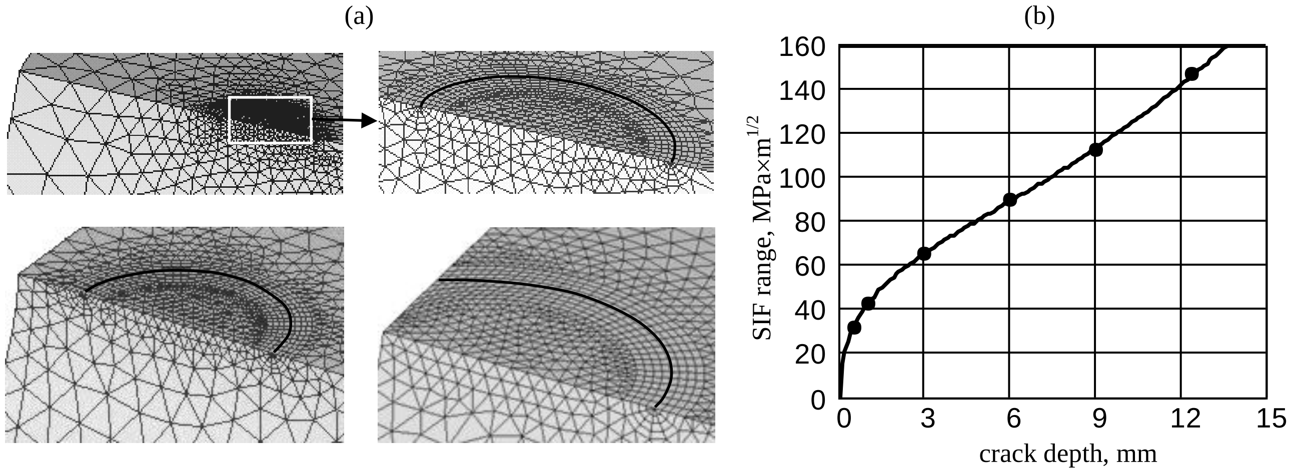

Fig. 4. Calculation of Stable Fatigue Crack Growth of in the Turbine Disk:
a) – Fragments of Finite Element Models of Disk having Cracks of Depth *1*, *3* and *6* mm;
b) – $\Delta K(l)$ Dependence (Calculated Points and Approximating Function)

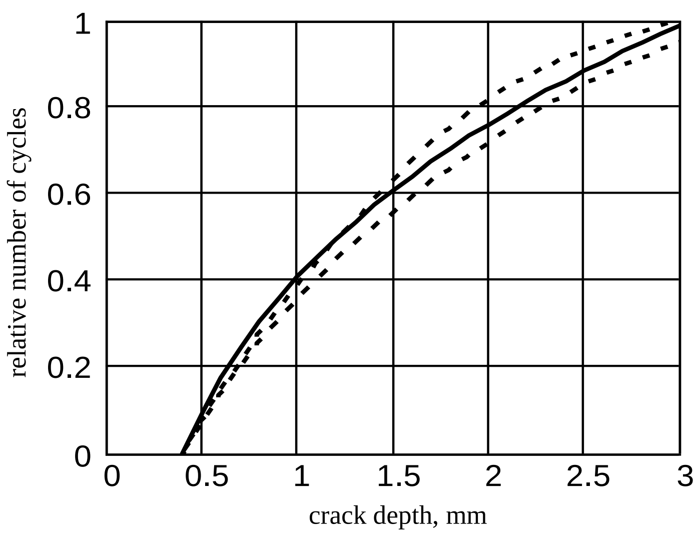

Fig. 5. Verification of Stable Fatigue Crack Growth Calculation in the Turbine Disk: Calculated (Continuous Line) and Experimental (Dotted Lines) Dependencies of Stable Crack Growth Period on Crack Depth.

determination of $\Delta K(l)$ dependence (fig.4).

- Calculation of experimental (6) and calculated (7) periods of stable crack growth (fig.5: $l_0=0.4$mm corresponds to depth of "technical" crack).

As seen from Fig.5, experimental values of stable crack growth period in disks investigated are close among themselves (such reproducibility of stable crack growth provides a possibility of its reliable prediction by calculation) and correlate well with calculation results.

The approaches discussed above have been used successfully for assessment of residual life and validation of periodicity of inspections of several disks of engines of different application under service conditions.

4 Summary

Method of safe inspections intervals evaluation is developed. The method is based on microfractographic reconstitution (using the results of electron microscopic analysis of a fracture surface microrelief) and calculated prediction of fatigue cracks kinetics under simple and complex loading cycles typical for civil and military aero engines.

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