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CALCULATED FORECAST OF CYCLIC LIFE FOR GTE DISKS, MANUFACTURED FROM TITANIUM ALLOY BEFORE AND AFTER CRACK INITIATION

Denis Slobodskoy, Alexandr Pakhomenkov, Rustam Azimov
NPO SATURN
Rybinsk, Russian Federation

ABSTRACT

GTE life as a whole and its components in particular is one of the main commercial criteria of a product, influencing its operation cost. At the moment the designers tend to increase the accuracy of calculation definition of main GTE part cycle life, what promotes to decrease the costs at the stage of designing and operating of products. In this work there has been presented a process of calculation definition of compressor disk cycle life before and after crack initiation. Calculation results are compared to the test results of a real GTE disk at the special test bench. The work includes 6 stages.

Stage 1 – calculation definition of cycle life before crack initiation based on general statistic data of material properties.

Stage 2 – tests of compressor GTE disk at a special test bench according to the program equal to a working cycle.

Stage 3 – calculation definition of fatigue crack propagation based on general statistic data of material properties.

Stage 4 –definition of actual disk material properties.

Stage 5 – fractographic investigation of the crack propagation zone, received during disk test.

Stage 6 – specifying LCF calculation and crack propagation calculation using the material properties obtained at the stage 4.

ABBREVIATION

FEM	Finite Element Model
GTE	Gas-turbine engine
FPI	Fluorescent penetrant inspection
FCG	Fatigue Crack Growth
SIF	Stress Intensity Factor
LCF	Low-cycle fatigue

NOMENCLATURE

KI	Stress Intensity Factor for Mode I
KIc	Critic Stress Intensity Factor for Mode I
$\Delta\varepsilon_t$	Range intensity of full deformations in a load cycle
N	Number of load cycles
Ψ	Relative contraction of material
E	Young's modulus
σ_a	Alternate stress of load cycle
σ_B	Strength limit of material at stretching
Θ	Angle
Θ_{kink}	Crack angle of turn
C, n	Coefficients in the Paris's equation
ΔN	Calculation spacing (number of load cycles)
ΔK_i	SIF range at the calculation spacing
Δa_i	Crack growth at the calculation spacing

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INTRODUCTION

Calculation definition of cycle life of main parts is the main task when designing and developing GTE. The service life depends on the accuracy of cycle life definition and correspondingly the cost and marketability of the whole engine. Modern LCF calculation methods provide quite high accuracy what allows to decrease accepted strength margins.

To ensure safety operation it is necessary to hold periodical damage and crack inspections. The periodicity of holding these inspections is also defined by calculation methods and is limited by crack propagation time from minimum discovered sizes to a critical value, which leads to demolition of a part. More accurate definition of crack propagation time till critical sizes allow to minimize accepted margins and increase the time intervals between the inspections what cuts the cost for GTE operation support but at the same time to provide the safety requirements.

Stage 1. Calculation definition of life

At this stage finite-element model of the disk with blades simulators (figure 1) has been developed according to test set up. Rotating blades in the test were replaced for mass-inertial simulators (with identical weight and inertia moments) to decrease aerodynamic resistance and intake power of test bench. Contact iteration between the blade imitator and the disk. Taking into account cycle symmetry of working blade elements, the calculation model has been performed in a shape of a sector of the working blade with an angle in one rotating blade. The model is performed by linear elements SOLID185 and includes about 250 000 degree of freedom. The model is fixed at the flange (for axial and tangential directions) and maximum rotation frequency is assigned.

The calculations were done taking into account the elastic material properties neglecting plastic deformation, as the further calculations of crack propagation use linear elastic fracture mechanic. The temperature during the tests doesn't exceed 80°C.

Stress-strain state calculations of the construction were done in the condition of maximum rotating speed at testing in program ANSYS [1]. Distribution of maximum main stresses in the disk is shown in the figure 2. Peak stress level is situated in the corner of dovetail slot from the entrance side.

Based on the received stress-strain state the evaluation of cycle disk durability on cycle 0-MAX-0 was done, according to the test set up. Evaluation of cycle durability has been performed based on general statistic data about material properties using analytical dependencies of Busquin-Manson-Coffin [2]:

$$\Delta\varepsilon_t = \left(ln\frac{1}{1-\psi} \right)^{0.6} \cdot N^{-0.6} + \frac{3.5}{E} \cdot \left(\sigma_B - \sigma_a \right) \cdot N^{-0.12}$$

Amplitude intensity of full deformation $\Delta\varepsilon_t$ has been defined taking into account elasto-plastic components, which were received out of elastic deformation von Mises from FEM using Neubers rule.

At that, calculation cycle durability was 4891 cycles.

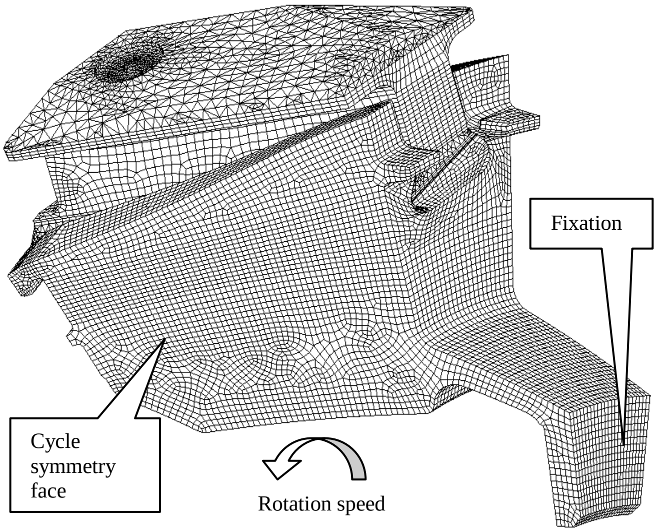

Figure 1 – External view of calculated FEM

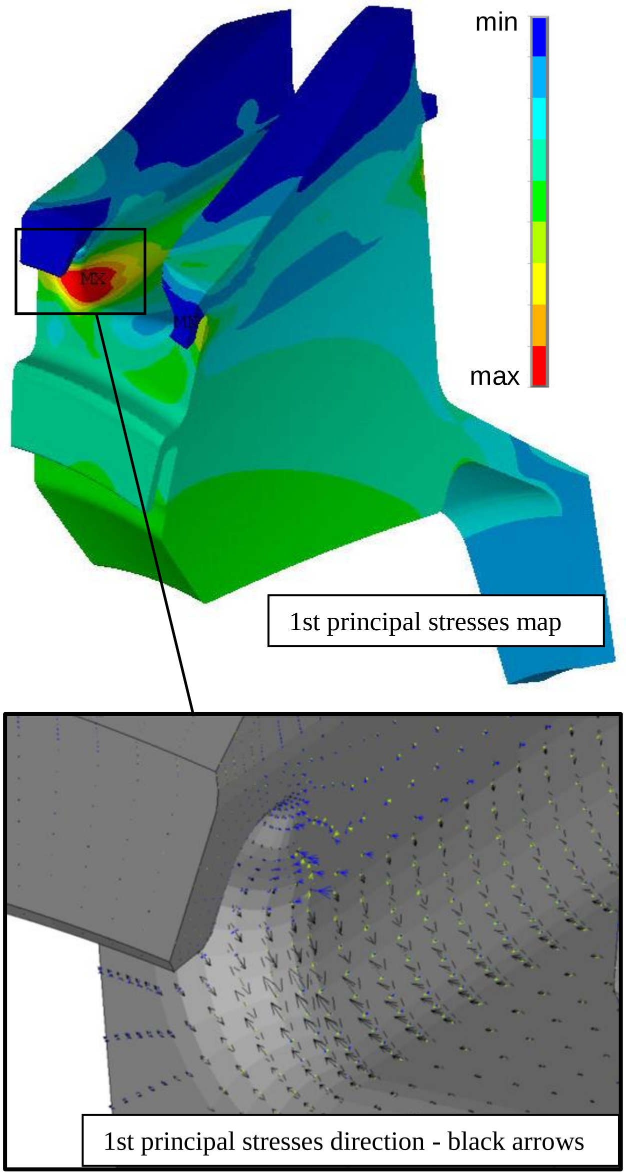

Figure 2 – 1^{st} principal stresses

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Stage 2. Conducting the tests

During the test a working blade was fixed on the bench and the spin-up was done till the maximum operation rotation time-lagged. Test cycle of load is identical to a real cycle at GTE work (figure 3). Rotating blades in the test condition were replaced for mass-inertial simulators (as it was mentioned above). The tests were performed into two stages: the tests before crack detection and tests with a crack.

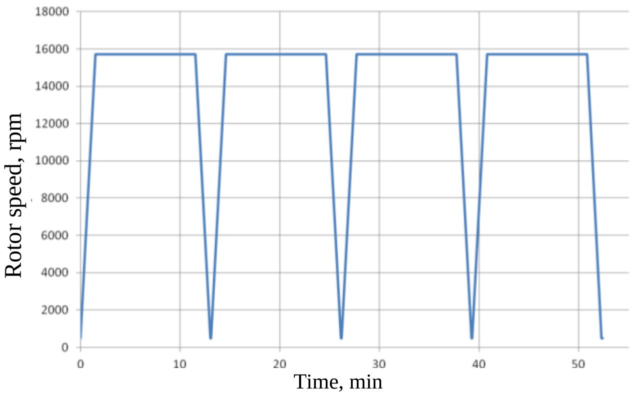

Figure 3 – Cyclogram of disk tests

Test before the crack detection

During the tests ever other 250 load cycles the periodical FPI-inspection was performed in order to discover cracks on the part surface. Cycle operation time of the disk till the moment when the crack has been discovered was 9442 cycles. The cracks have been discovered in the corner of dovetail slot from the entrance side what corresponds to the most loaded zone of the disk (figure 4). The size of the crack was about 8,0 mm along the slot and 3,0 mm along disk face.

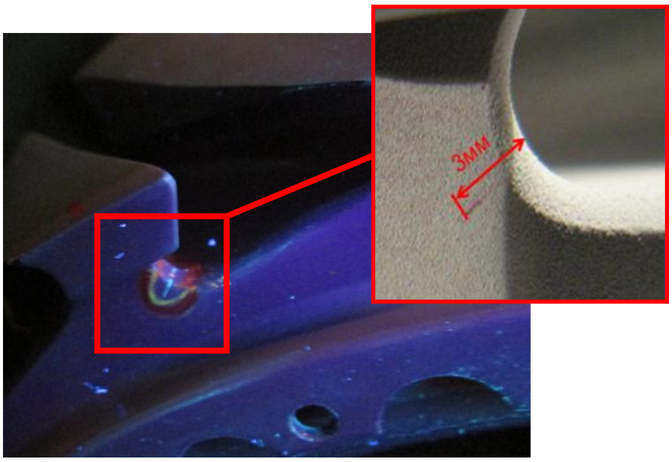

Figure 4 – External view of discovered crack

Tests with a crack

After the crack has been discovered the cycle tests were continued. During the tests every other 50 load cycles periodical FPI-inspection was done and every other 25 cycles visual inspection was done in order to watch the crack propagation rate. The tests continued till the moment when the length of the crack was close to the critical size (calculation critical length is 12 mm along the slot – see stage 3). According to the results it can be seen that propagation rate along the slot is faster than along the face. As a result the disk with cracks worked 600 cycles more till the tests were stopped. Final view of the cracks is shown in the figure 5. The size of maximum crack was 11,0 mm along the slot and 4,0 mm along the disk face.

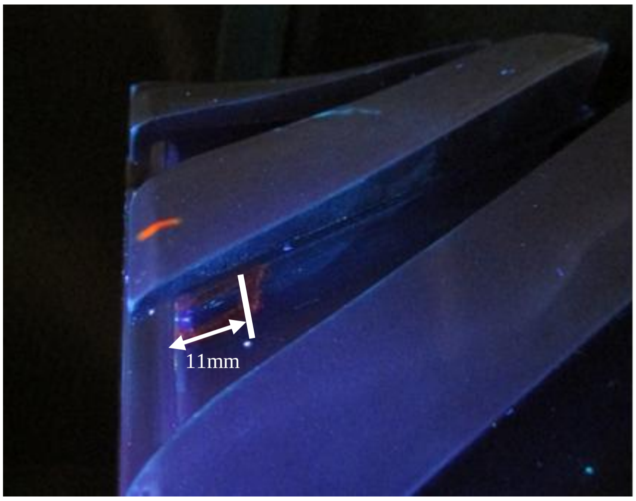

Figure 5 – Disk with operation time of 600 cycles after crack has been discovered.

Stage 3. Calculation of crack propagation

The sizes of initially exposed cracks at stage 2 were accepted for the further calculation of fatigue crack propagation. For calculation analysis of crack propagation rate average statistic material properties were used as well as the following program software: DARWIN и FRANC3D.

Program DARWIN [3] uses analytical dependencies and calculation results of strain-stress state to define SIF and crack propagation rate. DARWIN also cannot take into account the change of crack propagation direction (crack comes out of the limits of original flatness) [4]. Results of modeling showed that it takes 200 load cycles for a crack to reach its critical size At that the critical size was about 10 mm along the slot and is determined by reaching of critical SIF. Dependency of maximum SIF on number of load cycles is shown in figure 6.

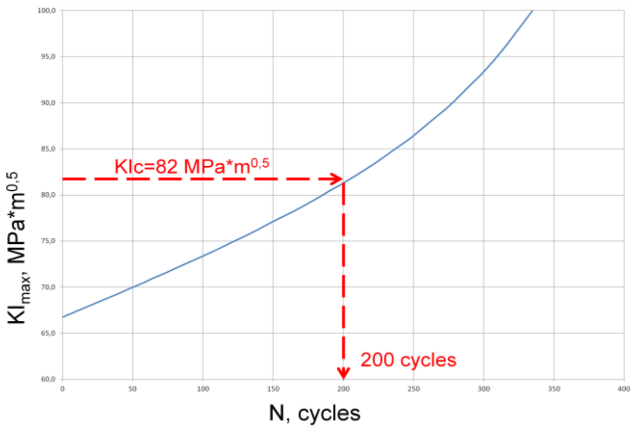

Figure 6 – KI_{max} vs. N

Program FRANC3D [5] uses direct 3D modeling of FEM crack front and numerical methods of SIF definition in each of the points of the front and space reconfiguration of the front at each calculation iteration [6, 7]. Modeling results showed remaining life with a crack more than 800 load cycles. At that the final size of the crack was about 12,0 mm along the slot. In figure 7 calculation crack fronts are shown. Lines in figure 7 show the crack front after every 100 loading cycles. Lower

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boundary is dovetail slot surface, upper boundary is disk frontal surface.

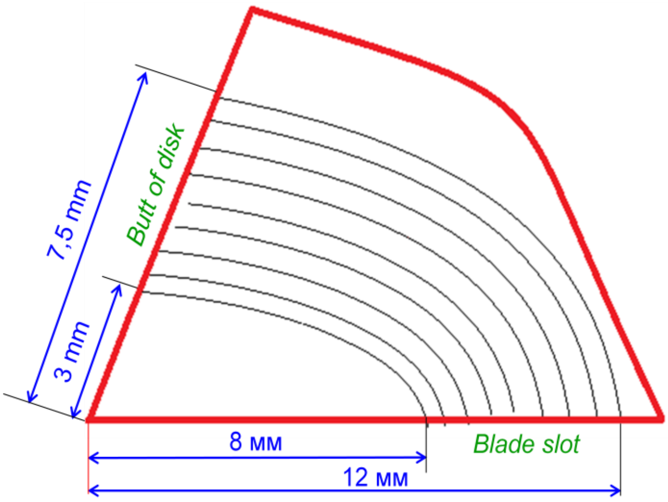

Figure 7 – Calculation crack fronts.

SIF values in each crack front point are shown in figure 8. On abscissa there is presented the value of normalized distance along crack curved front. On ordinate axis SIF value is placed. Each line at the figure corresponds to crack front after every 100 loading cycles. Based on calculation results, there can be observed SIF decrease from the side of disk face (FCG slowdown) and SIF increase from the side of dovetail slot (FCG speed up).

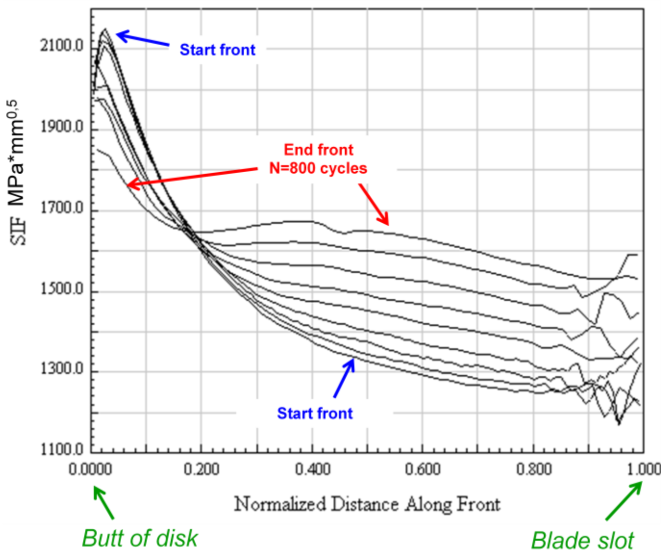

Figure 8 – SIFs for crack fronts

Change of crack propagation direction (angle of deflection from initial direction Θ_{kink}) was calculated by built-in algorithm of program FRANC3D with use of Maximum stress criterion at every calculation spacing [6]:

$$\theta_{kink} = \theta \text{ such that } \sigma(\theta)\big|_{max}$$

Calculation of crack propagation was performed with the help of Paris formula also with built-in algorithm of program FRANC3D:

$$\Delta a_i = \Delta N \cdot C \cdot (\Delta K_i)^n$$

During the propagation the crack changes its direction and comes out of the limits of original flatness. In figure 9 the visualization of final crack front *N*=800 cycles is shown.

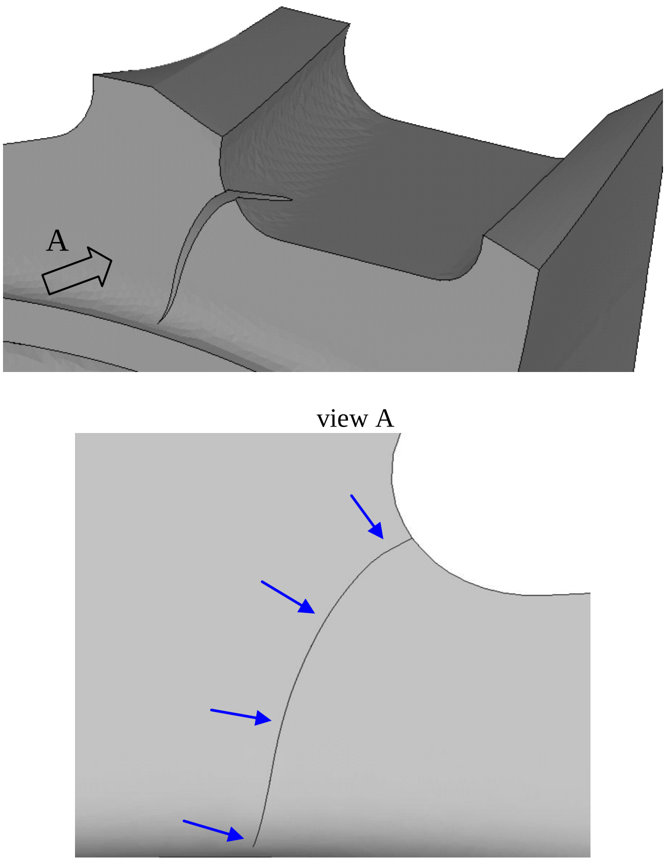

Figure 9 – Visualization of crack front
N=800 cycles

Modeling in program DARWIN showed more conservative results comparing to numerical calculation of FRANC3D, determined by the calculations only in original defined flatness (direction of propagation), while numerical calculation showed the change of crack propagation direction.

Stage 4. Investigation of disk material properties

To define actual disk material properties there was performed slitting cut of the disk, which passed the test, with the purpose to produce the samples to define characteristics of short-time strength, low-fatigue cycle and fatigue crack propagation rate [8]. The direction of cutting corresponds to the direction of maximum active stresses in corresponding disk zone. The scheme of disk slitting cut is shown in figure 10. In total there were received 5 samples for the short-time strength tests (see figure 11), 38 samples for low-cycle fatigue tests (see figure), 4 samples for crack propagation rate tests (see figure 12).

As the part worked at relatively low temperatures (around 60-80 °C) the investigation of material properties was done at temperature 100°C. Tests on definition of low-cycle fatigue characteristics and crack propagation rate were performed according to the requirements [9] and [10] correspondingly.

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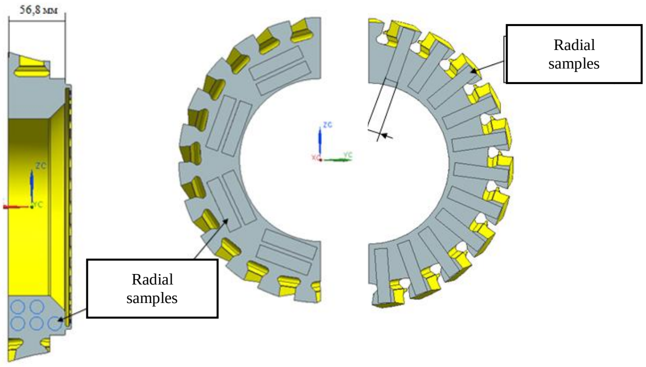

Figure 10 – Scheme of disk slitting cut

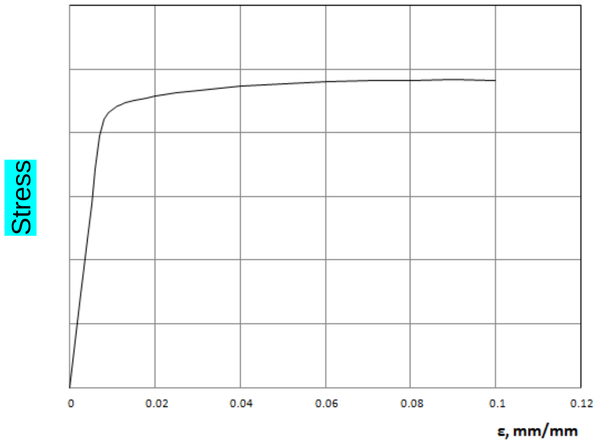

Figure 13 – Deformation curve

Figure 11 – Sample for short-time strength and low-cycle fatigue tests.

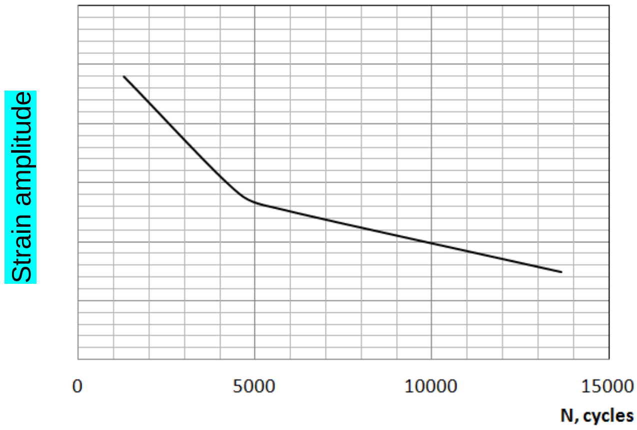

Figure 14 –LCF curve

Figure 12 – Sample for FCG tests.

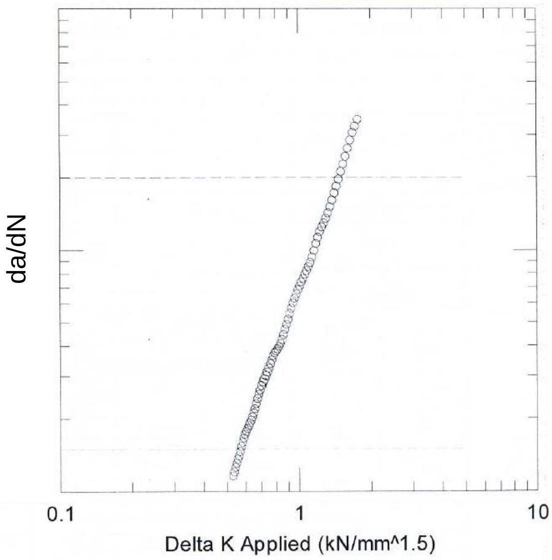

Figure 15 – Diagram of crack propagation rate

Results of the tests on short-time strength are shown in figure 13. LCF curve is shown in figure 14. Kinetic diagram of crack propagation rate is shown in figure 15.

Stage 5. Investigation of crack fracture

When the tests of the disk were completed, the slitting cut of the zones with cracks was done followed by their disclosure. The images of the crack fracture for different dovetail slots are shown in figures 16-17.

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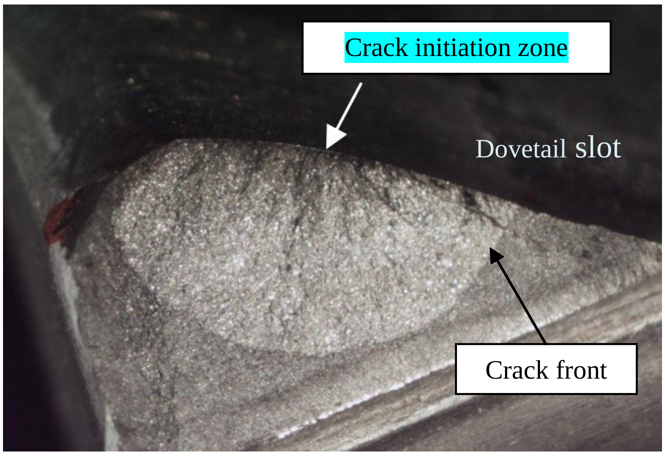

Figure 16 – External view of crack fracture in dovetail slot №3

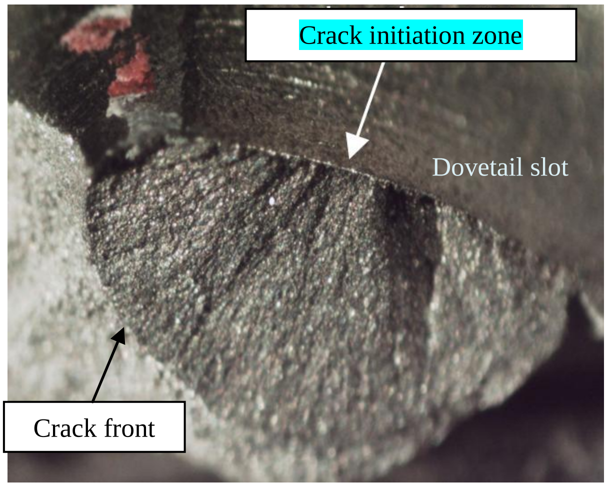

Figure 17 – External view of crack fracture in dovetail slot №7

After the crack has been disclosed there was performed analysis of disposition and forms of the crack fronts according to fractographic investigation [11]. Based on analysis results the crack has classical elliptical shape. Crack initiation zone is situated in the angle of dovetail slot and corresponds to the zone of maximum stresses in calculation model. Direction of crack propagation is perpendicular to influence of calculated 1^{st} principal stresses, what corresponds to the expectations. The step of crack fronts is also identical to the one predicted at stage 3.

Stage 6. Specification of the calculations according to the actual material characteristics

Based on the data from strain-stress state with the use of actual low-cycle fatigue characteristics there was performed specified calculation of disk cycle life till the crack initiation. Specified analysis was performed with appliance of low-cycle fatigue curves, determined from actual disk material properties. Based on analysis results there was defined that calculated life is 8300 cycles. Obtained calculated value of life before crack initiation has higher level of correlation with the experiment results. Difference between actual and calculated life is about 10%, at that original analysis with the use of Busquin-Manson-Coffin equation showed deviation about 50%.

Also there was performed specification of calculation of crack propagation with use of received actual material properties. Specified value of cycle numbers till the crack reaches the critical size is around 250 cycles for program DARWIN and around 1000 cycles for program FRANC3D.

CONCLUSIONS

1. Using of Busquin-Manson-Coffin equation for defining cycle life gives significant underrating of the results, what provides additional conservatism when nominating the part life and doesn't reflect the reality. To provide the maximum accuracy of cycle life definition and cost reduction on maintenance, in modern GTE it is required to make overall fatigue investigation of materials.

2. Classical methods of calculations of crack propagation in flatness in some cases can give significantly lowered results what can also lead to increase of the costs for GTE maintenance. For dangerous zones of the parts with complicated stress-strain state in which the minimum time intervals between inspections were defined (with the help of crack propagation calculation) it is reasonable to use 3D modeling methods of crack propagation in order to specify the calculation and increase the time intervals between inspections(for example, to use FRANC3D).

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