Crack Path for In-service Subsurface Fatigued Turbine Blades

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ABSTRACT. *The Very-High-Cycle-Fatigue (VHCF) regime of in-service turbine rotor blades of the superalloy GS6K was considered based on tests data for specimens of superalloy EP741 NP in the case of environment temperature 650^0C. Crack origination in aircraft engine blades has occurring subsurface because of in-service their resonance with frequency approximately 4 kHz during flight under the biaxial cyclic loads of bending-torsion with tension. The material pressing and torsion during crack origination in one of the grains is main mechanism of material subsurface cracking. Crack propagation in-flight takes place with two types of meso-beach-marks formation. The discovered crack path features have been considered, selected and crack growth period in the range of 120 and 160 flights was demonstrated for in-service blades. The stress equivalent for the crack origination in VCHF regime was calculated based on of the well-known Murakami's* $\sqrt{area}$ *- model. It was shown that better stress level estimations ought to be considered with factor 1.0 for the discussed blades failures under biaxial cyclic loading.*

INTRODUCTION

Turbine rotor blades (TRB) operated in civil aircraft engines under gase environment with temperature in the range of 650^0-750^0 C. That is why different types of superalloys used for TRB design [1].

Main criterion used for TRB in-service lifetime estimation based on consideration creeping process. TRB critical state has to be estimated with this process till the design-service-goal which expected in-service not less than 10000 hours.

Inspite of the creeping criterion, it ought to be considered blade vibrations under gase stream which influenced fatigue damages accumulation in the operated TRB and can limited in-service lifetime for them. Blades vibrations can occure during short period with high frequency because of effect of resonance but its influence has not to be dominant in operated TRB with typical complex loading in-flight cycle.

Usually, in-service turbine blades fatigue cracking is the second stage after the first creeping process. These two processes always bordered strongly expressed difference in crack path. Material intergranular cracking due to creeping process takes place on the first stage of material cracking but the transgranular cracking with meso-beach-marks formation occurred on the second stage of TRB cracking because of fatigue.

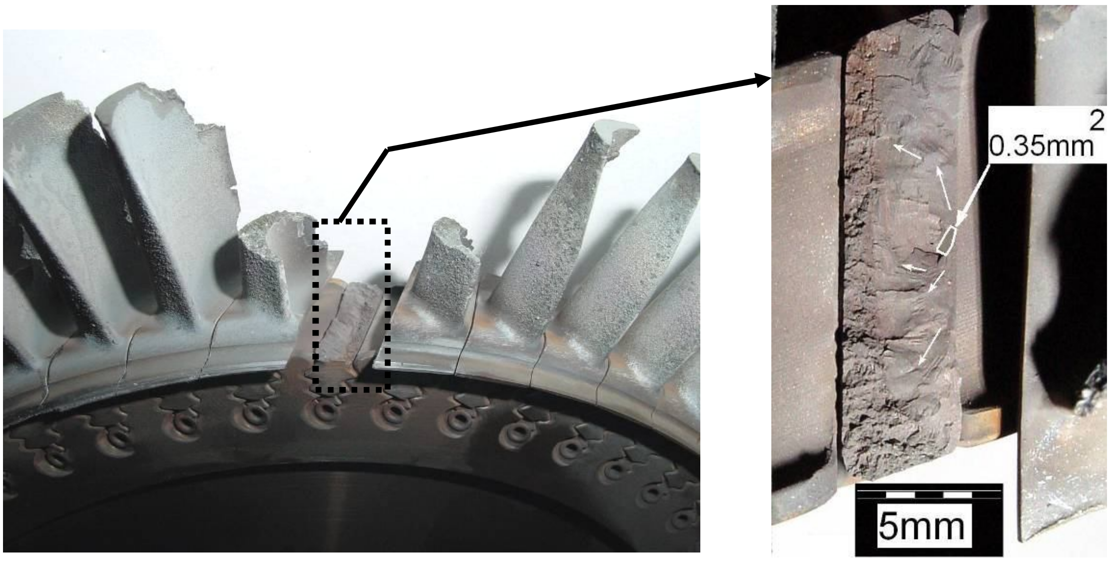
Neveretheless, to extend in-service lifetime for aircraft engines new materials prepared by advanced processing techniques that significantly reduce the content of microstructure heterogeneities are expected to be the main crack initiation sites [2], [3]. They considered for turbines disks to use in Very-High-Cycle-Fatigue (VHCF) regime. In this regime, fatigue crack initiation (rather than crack propagation) is thought to be the life determining process more now introduced poader technology.

Concequently the creeping criterion has to be corrected, and more complicated case of creeping-fatigue damages accumulation must be considered.

In fact, TRB are permanently heated and statically stretched by the centrifugal forces, controlled by the revolution speed of the rotor. Under such conditions, thermally activated creep-fatigue effects become possible within each-flight loading cycle.

For in-service engines of M-601 there were seen rear cases of TRB in-flight fatigue failures with subsurface crack origination (Figure 1). The fatigued blades of various engines had flown in the range of (370-1670) hours at the moment of their failure ispite of disign-service-goal not less than 10000 hours. That is why first thinking about cause of the TRB failures was addressed to creeping process for the crack subsurface origination because of bad state of manufactured superalloy GS6K. This consideration was used to improve technology for TRB but rear failures had appearing again with the same evidence of subsurface fatigue crack origination.

Neveretheless, special new investigations of crack path for the TRB of engine M-601 have been performed to exclude their in-flight failures. Below results of these investigations will be considered.



a) b)

Figure 1. Overwiev (a) of the tubine disks with area of first failed and other damaged blades and (b) macroscopic view of this blade fracture surface with indication in squer are of the crack origination (white arrowths show directions of crack propagation).

INVESTIGATION PROCEDURE OF TRB

The superalloy GS6K used for preparing TRB. GS6K is strengthened primarily by precipitation of a gamma prime phase (γ’). Figure 2 shows the typical microstructure of the alloy.

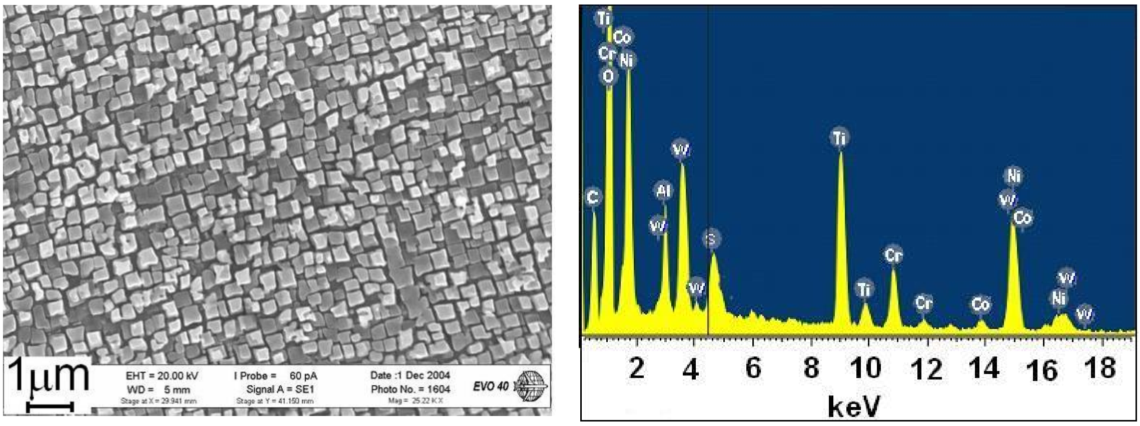


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Figure 2. Typical (a) microstructure of GS6K alloy with indication of gamma prime phase (γ’) shapes, and (b) example of chemical elements distribution in area of crack origination.

Microstructure of all discussed TRB, fatigued in service, has been attested with scanning electron microscope under magnification not less that 10000 times and it was shown that in each case studied the variation in shape of γ’-phase was not principle from shown in Fig.2. The distribution of grain size and the mean grain size were in the same range that recommened by the introduced manufacturing procedure for TRB.

Material average chemical composition has been compared with their local distribution based on the X-ray analyses in scanning electron microscope with using special device of INCA-instrument, see Fig. 2b. Results of the analyses have shown that by the main chemical elements there not principal difference in their distribution as recommended for investigated superalloy GS6K.

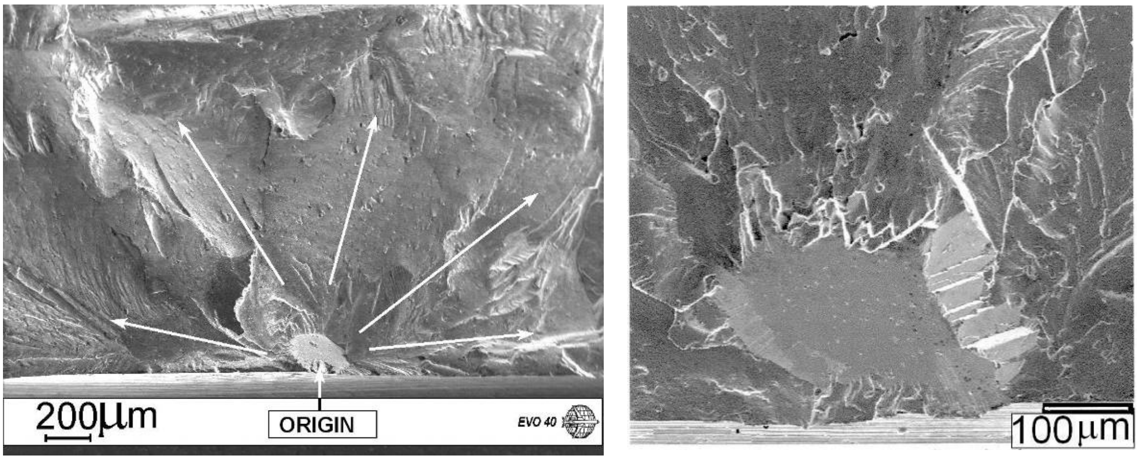
In-service TRB experienced loads frequency under bending-rotating from the gase stream approx. 4 kHz. That is why the lifetime to failure for all fatigued blades took place in the VHCF regime: (4000 x 3600 x [370-1670]) = (0.53-2.4) x 10^{10} cycles.

Fracture surfaces have been analysed in scanning electron microscope of Carl Zeiss instrument. Discovered during TRB investigations fracture surface features have been compared with earlier disussed fracture surfaces of EP741 NP superalloy [3]. This superalloy was prepared by powder metallurgy techniques that significantly reduce chemical inhomogeneity and initial defect sizes in the alloy. The metallurgical procedure for the EP741 NP was not the same that for TRB of M-601 engines but the chemical compositions and γ’-phase were the same for these two materials. That is why the fracture surface features in VHCF regime were compared for these superalloys.

RESULTS OF TRB INVESTIGATION

Fatigue crack origination

Fractographic analyses of in-service failed TRB have shown that the crack origination in all cases took place not far from the blade surface, Fig. 3.



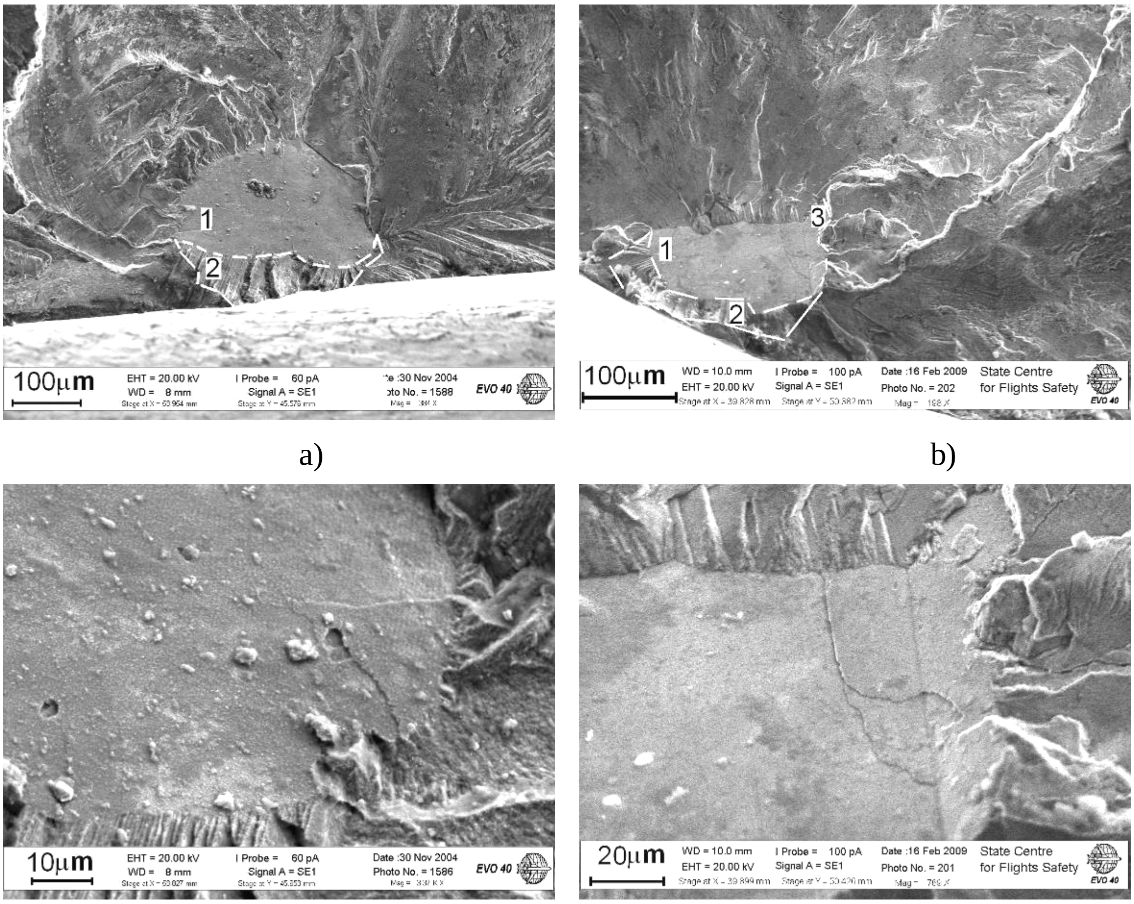
a) b)

Figure 3. Areas of fatigue crack origination in TRB after in service time (a) 1493 hours or 1084 flights and (b) 370 hours or 264 flights.

First flat facet (FFF) is the main fracture surface pattern for all blades which reflect first step of TRB fatigue cracking independently on the in-service number of flights or operating hours. Cracks have origination in one of the points by the border of the grain or through grain without formation point of origin. Two grains had quasi-brittle cracking with strongly expressed border which devided subsurface and surfacesly TRB fatigue cracking. That is why below will be considered more precisely only features for in-service failed TRB which had flown 1493 hours.

Features of the fracture surface in FFF for TRB have been compared with subsurface pattern of fracture origin areas of EP741 NP alloy specimens fatigued in the stress transition range from VHCF regime to High-Cycle-Fatigue (HCF) regime, Fig. 4. It is clear that compared features of the FFF are the same in both cases. The subsurface FFF has strongly expressed border because of transition from one to another mechanism of material cracking. The similarity in fracture surface features for all FFF reflectes the unified mechanism of subsurface metals cracking. It was discussed earlier applicably to Ti-, Al- and Ni-based alloys [3]–[5]. The mode-III mechanism of twisting under compression is the way of the crack subsurface origination for metals in VHCF regime. The FFF subsurface formation starts because of material cyclical weakness in a local volume under compression with twisting due to residual stresses and, simultaneausely, diffusion in the weakened volume rest gases or other chemical elements.

FFF on the discussed TRB fracture surface has regular lines but on the specimen FFF there not seen this pattern (see Fig. 4c and 4d). This is not sistemaric behaviour for blades fracture surface formation.



a) b)

c) d)

Figure 4. View areas of subsurface FFF in the in-service failed (a), (c) turbine blade and (b), (d) in-test fatigued specimen of EP741 NP superalloy formed respectively after in service time 1493 hours or 1084 flights and $9x10^5$ cycles with stress level 960 MPa and R=0.05. Numbers “1”, “2”, “3” indicate cracked grains. Photos (c) and (d) are magnified view of (a) and (b) respectively.

In many cases FFF were with the same smooth surface that is shown in Fig. 4d. The regular lines reflect plastic relaxation acts due to persistence slip bands mouving after the FFF formation. For instance, these patterns were seen for fatigued Ti-based alloy with subsurface cracking on the one fracture surface but had not seen on another one [5].

Nevertheless, concluding remarks have to be done that TRB fatigue cracking takes place in VHCF regime because of specific fracture mechanism which directed to FFF subsurface formation due to the mode-III mechanism of twisting under compression.

Fatigue crack propagation

In VHCF regime of specimens there can be seen short period crack propagation inspite of dominant period of crack origination [6]. The dominating of crack origination period has evidens for full subsurface fatigued specimens.

TRB subsurface cracking took place in the area of two or three grains only, and, then, through crack propagation has occurred with semi-elliptically shaped crack front. That is why it was interesting to estimate number of flights for cracked TRB in VHCF regime but for the stage of surfacesly crack propagation.

The well-known pattern as meso-beach marks were performed on the TRB fracture surface because of material simultaneously cracking under mode I and II, Figure 5.

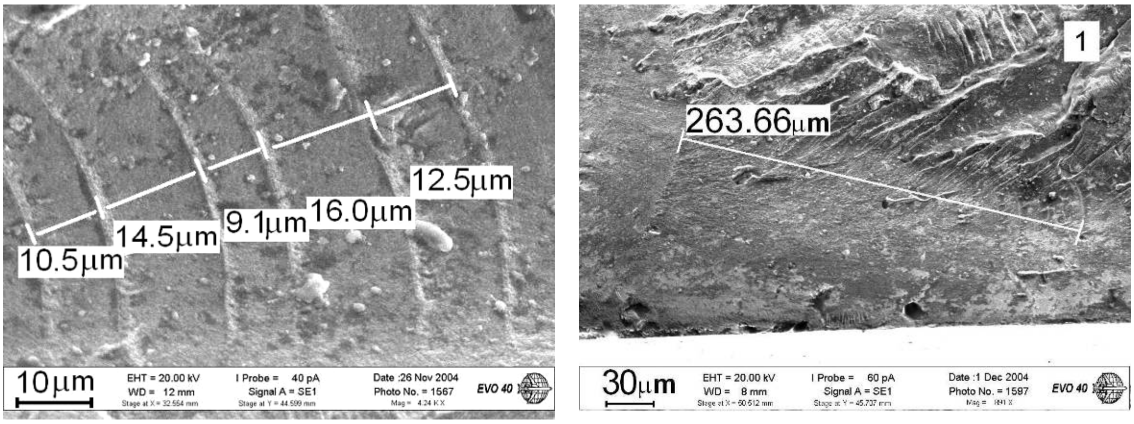


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Figure 5. Two types of meso-beach-marks have been indicated as (a) – MBM1, and (b) – MBM2, having difference in spacings.

There were discovered two types of meso-beach-marks (MBM): (1) MBM1 with small spacing; (2) MBM2 with larger spacing which included itself some number of MBM1 with small spacing. The MBM formation process had so regular manner that the MBM2 in a number of 8-12 could be systematically seen as one block for one MBM1 (see Figure 5). The block of MBM1 reflects the blade material reaction on the cyclic loads variation during fatigue crack propagation in one flight [1].

As a result of the measurement MBM1 spacing and calculations number of cycles, $(N_p)_1$, the unified dependence of the MBM1 spacing and $(N_p)_1$ on the one of the semi-crack-length along the TRB surface was discovered, Fig. 6.

The crack has only propagation in blades during a short part of a start-and-stop cycle of the engine. Number of these short periods reflected number MBM1 between two MBM2. Each flight-cycle directed to crack propagation and the crack increment leaves between the two MBM2 lines [1].The ratio one to ten between number of MBM2 and MBM1 has been used to calculate number of TRB flights which was in the range of (120-160). This period for the investigated TRB has not principal difference with the earlier established interval 80-200 flights for in-service fatigued blades of superalloys which failures took place at a number of cycles more than 109 flights [1,2].

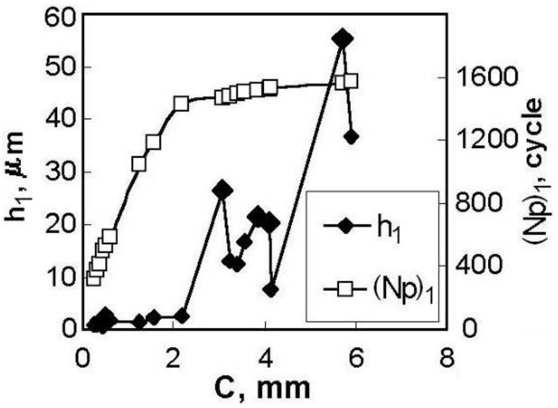

Figure 6. MBM1 spacing h_1 and number of cycles $(N_p)_1$ versus crack length "c" in the direction of crack propagation from origin on the maximum distance to fast fracture.

The ratio N_p/N_f between crack growth period and lifetime to failure for TRB was [160/1084]x100%= 14.7%. Consequently, in the VHCF regime there is the ratio N_p/N_f being approximately the same that in the HCF regime after subsurface cracking has transition to through crack propagation.

Stress level

The TRB stress state is biaxial bending-torsion in the section of the blade fatigue failure with principal stress ratio near to σ_2/σ_1 =0.3. This value was used to estimate the stress equivalent value on the basis of the data base taken from the paper [7]. There were introduced diagramm for different flaw sizes and the stress equivalent value, $(\sigma_e)_1$, at different biaxial stress ratios in the paper. The FFF-area-size of investigated TRB was used for $(\sigma_e)_1$ estimation. The discovered value was near to 230MPa ispite of designed value not more than 48 MPa.

That is why the fatigue limit σ_w of the in-service TRB was evaluated by the Murakami $\sqrt{area}$ – model [8]:

$$\sigma_w = [k_p=1.56](HV+120)/(\text{area})^{1/6} \tag{1}$$

In the invested case, parameters of the Eq. (1) are HV=430, and $\sqrt{area}$ = (235 μm and 350 μm) for TRB areas shown in Fig. 3. Calculated values of the equivalent stress are near to 317 MPa and 345 MPa respectively for TRb with in-service time 1669 и 370 hours. In the case of k_p=1.0 stress level for TRB is in the range of (210-230) MPa being not far from the calculation result based on the database taken from the paper [7].

DISCUSSION

The designed stress equivalent for TRB was estimated near to 48 MPa for the introduced air stream with frequency near to 4.1 kHz. The resonance frequency for number of TRB was estimated near to 4420 Hz. That is why it can be done conclusion that some of the TRB can has experience of high level of cyclic stress due to resonance.

To support this conclusion it was estimated accuracy for measurements of frequency average values of 4050 Hz and 4420 Hz respectively for air stream and TRB resonance. Measurements method has accuracy not less than 3%. Therefore, there can be seen for blades introduced maximum frequency [4200 + (4200x0.03)]=4326 Hz and the minimum resonance frequency - [4420 – (4420x0.03)] = 4288 Hz. Evidently that small part of the in-service TRB can have experience the resonance regime of cyclic loading which can be in several times more intensive than with designed value of 48 MPa. Appearance of these cases in-service is very rare situation for TRB. That is why in-service fatigue failures of TRB were very rare events.

CONCLUSION

The in-service fatigue failures of the blades in VHCF regime takes place because of the TRB resonance. The crack origination was just subsurface with the place for point of origin not far from the 50 μm. The crack propagation regularities for in-service fatigued TRB such as different in spacing meso-beach-marks were discovered and the number of cycles during fatigue crack growth period was calculated. The calculated number of flights during surfacesly fatigue crack propagation was in the range of (120-160). The calculated stress equivalent value from the fractographic analysis for the blade resonance regime of cyclic loads was in the range of 210-230 MPa.

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