CRACK PATH OF IN-SERVICE FAILED TITANIUM COMPRESSOR DISKS IN HIGH- AND LOW-CYCLE-FATIGUE REGIME

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ABSTRACT. *The fatigue crack path for titanium compressor disks in rim parts of aircrafts engines D-30 and D-30Ku of the first stage of the low-pressure compressor has discussed. Based on fractographic analysis shown that the high cycle fatigue regime is the first stage for in-service damage accumulation in the titanium alloy VT3-1 used for compressor disks manufacturing procedure. This situation took place in the case of cracks propagation in the perpendicular direction to the disks radius in disks of engine D-30. In disks of engine D-30Ku crack propagation took place along the disk radius. This situation is analysed based on results of numerical estimations of material stress-state and sequence of the crack path features for two stages of high cycle and low cycle fatigue regime for disks has shown.*

INTRODUCTION

The problem of in-service failure of titanium compressors disks has been earlier in details considered [1, 2] with reference to their hub parts. The main cycle of damages accumulation is the block of in-flight cyclic loads, which correspond, as a rule, all in-flight transition processes of aircraft loading sequently at take-off, cruising flight, etc. In the case of disks thickness less than 10 mm, blocks of cyclic loads, fluctuations reflecting directed to decrease the crack growth period, which cannot exceed 50 flights. It is High-Cycle-Fatigue (HCF) regime. For disks of the greater thickness, the main damage takes place from flight to flight that corresponds to the Low-Cycle-Fatigue (LCF) regime. In this case, process of disks fracture development can performs during several thousand flights.

Regular researches [2] of the in-service failed titanium disks have shown that their fractures at lifetime in some thousand flights reflected the bad material state of disks. In fact, disks material has sensitivity to the in-flight dwell-time of loading that leads to mainly brittle fracture with formation, so-called, facetted patterns of fracture surface. This type of fracture surface relief reflects shapes of two-phase globular or lamellar structure of titanium alloys.

The developed methodology [2] of the fracture surface analysis of the titanium disks, taking into account set of the mentioned above features of alloys behavior, allows to reproduce kinetic laws of fracture process taken place in disks hub parts and to estimate duration of crack development.

At the same time, in some cases are observed cracks origination [2, 3] in rim part of disks. In zones where cracks originate, the designed disks stress-state estimated only by the flight sequence of cyclic loads that corresponds to the LCF regime of the damages accumulation in material. However, actually, there are evidences to believe that such situation realizes not in all cases of titanium disks fracture by the rim parts. It is possible cyclic loading combination in LCF regime and in HCF regime. The specified assumption based on the following facts. (1) In LCF regime of the disk failure in one section, several cracks in other similar sections take place. However, a number of disks failed in rim parts only in one section. (2) Tests of disks at the LCF regime show [1] that cracks in them arise from a corner of rim-outshot. However, in a number of in-service fatigued disks cracks arose in a middle area at the surface by the basis section of rim-outshot.

The listed above features of disks in-service failures by the rim-outshot have demanded carrying out of special investigation to generalize of cracks path in the rim part of titanium compressor disks of gas-turbine aviation engines (GTE). Results of these investigations discussed this paper.

INVESTIGATION PROCEDURE

As objects of the investigation were used titanium disks of the first stage of low-pressure-compressors (LPC) of engines D-30 and D-30KU-154 in which cracks led to individual fracture in area of a rim-outshot without cracking of other rim parts.

Database for operating times of rejected during repair and used for investigation disks of engine D-30 are submitted in Table 1.

Table 1. Database for rejected during repair titanium disks of the first stage LCP of engines D-30 because of cracks in area of the rim-outshot

nn	Item of the engine	Operating time, hours / flights	
		Since new	Since last repair
1	MC0123003	10753/6995	1959/1230
2	ЛC0132032	12913/8632	1094/967
3	MC06103004	11498/7129	2232/1336
4	MC08103035	11881/7157	2108
5	MC04203057	15629/8842	1239/701
6	01112026	15991/9633	1709/1090
7	07202001	10322/6083	2814/1680

For engine D-30KU-154 several disks of first stage LPC has been considered. One of the presented below disk, at the moment of fatigue fracture has flown 17657 hours

(6020 flights) since it was new, including 2663 hours (888 flights) after the last (third) repair.

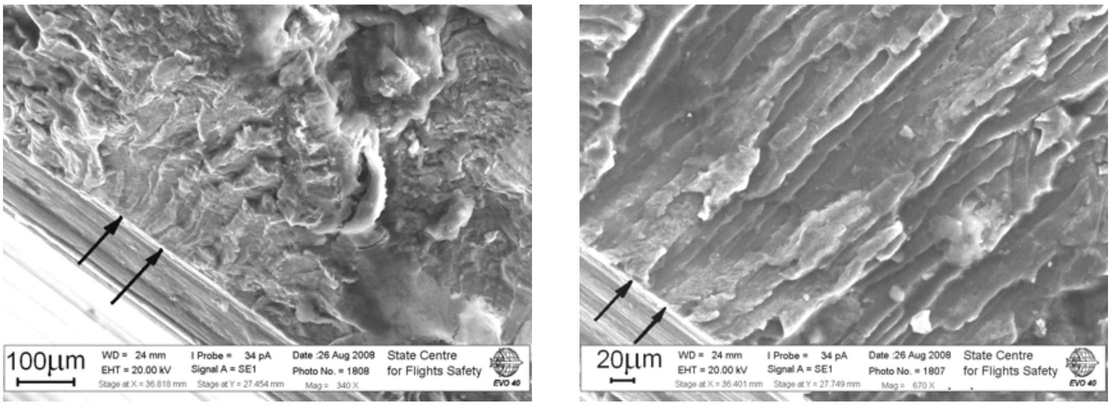
The titanium alloy VT3-1 used to manufacture disks of both engines. The material has the ($\alpha + \beta$) globular and lamellar microstructure. Tensile properties of the material are: ultimate tensile strength 1320MPa, yield strength 990 MPa and elongation 27%.

For all disks, scanning electron microscope EVO-40 having resolution not less than 3nm, with a Karl Zeiss facility was used to examine fracture surfaces. All features of the carrying out fracture surface analysis for titanium alloys described in [2].

CRACK PATH FOR DISKS OF ENGINE D-30

The database analysis has shown that with increase of the operating time since new, in terms of hours, the quantity of disks with cracks increases. It specifies that in a rim-outshot there is a steady tendency to achievement of the limiting condition at an operating time more than 20000 hours.

It has established that in all cases studied the initial zone of the fracture origin represents of the facet with specific relief, Fig. 1. There is relief, commonly desined “streamlet-like”, and lined surface of the facet. In all cases, the revealed surface pattern of the facet reflects the material fracture in HCF regime. They distinctly seen because of intersections of slip bands under sliding process that are typical characteristics of titanium alloys fracture in the HCF regime.



a) b)

Figure 1. Overview of the fracture surface pattern near origins (shown by arrows) of disks of engine D-30 taken an operating time (a) 11489 hours, (b) 11881 hours.

After the initial facet there was performed fracture surface with the similar relief which has been earlier discovered in disks hub parts - dominates facetted pattern, and in separate fracture zones there are blocks of fatigue striations. Localness of the specified fracture surface relief is so that separated fracture areas with fatigue striations make no more than 5 % from all fracture area. Nevertheless, in some fracture areas there are extending zones with fatigue striations where their number reaches several hundreds.

The principle difference in the fracture surface relief for all investigated disks is not present. The most extending zone of the initial facet developed in HCF regime has revealed in the disk with operating time 10753 hours. Here it was possible to see several meso-beach-marks (MBM) reflecting borders for crack propagation during one flight cycle indicated as “FC”, Fig.2. The most MBM quantity revealed on the initial facet has made 30 pieces that corresponds to 30 FC, according to the developed methodology [2] of cracks growth period estimation in titanium compressors disks.

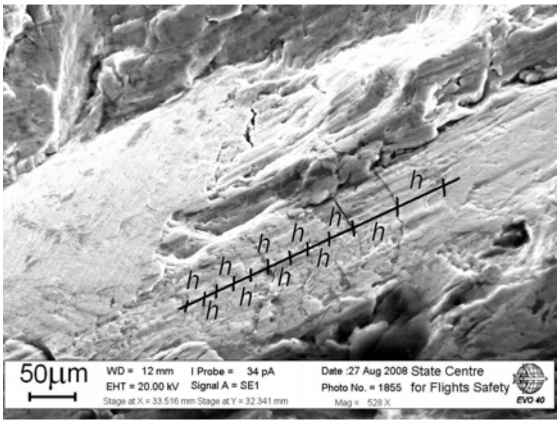


Figure 2. Blocks of meso-beach-marks of the spacing “h” in the damaged because of tearing area of the fracture origin of the disk with an operating time 10753 hours.

Attempts to estimate cracks growth duration in different disks have been undertaken based on measurements of fatigue striations spacing. However, localness of zones with blocks of fatigue striations and their unequivocal orientation concerning to initial fracture zone have not allowed to lead an estimation of cracks growth duration. The dominating fracture surface facetted pattern testifies because of action on the rim-outshot of loads from blade vibrations. In fact, duration of vibration loads cannot be estimate for one flight. Therefore, there are many facts to believe, that duration of cracks development through the section at the basis of the rim-outshot makes no more than several tens flights. This conclusion has aggrement with the earlier investigated failures [2] of rim-outshots of disks engines D18 and D36. Investigations have shown that crack growth period in the specified disks has made less than 90 flights.

FRACTURES ALONG RADIUS OF DISKS ENGINE D-30Ku

The crack path

The considered disk failure of the first stage of the LPC took place because of separation of disk rim portion with five blades. The beginning of the disk fatigue fracture has realized in area of the corner of the rim-outshot base, Fig.3. The fracture occurred on the intermediate surface between the rim-outshot surface and the groove surface for the blade. On the fracture surface there were good-looking macro-beach-marks (MABM) of the fatigue failure (see Fig. 3b).

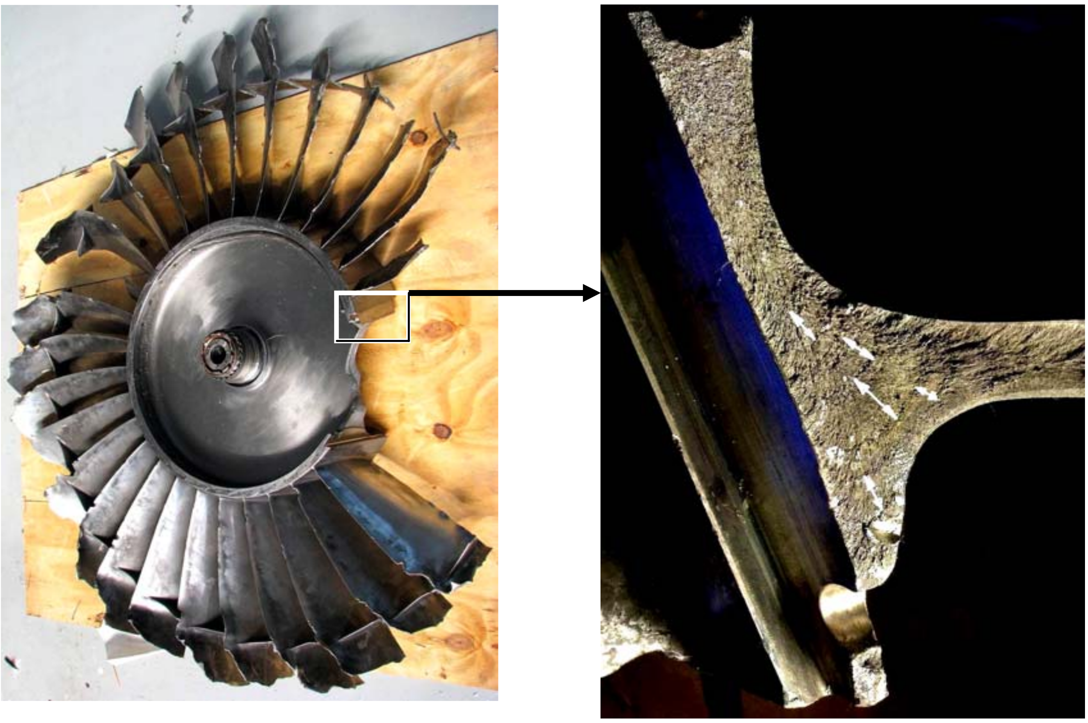
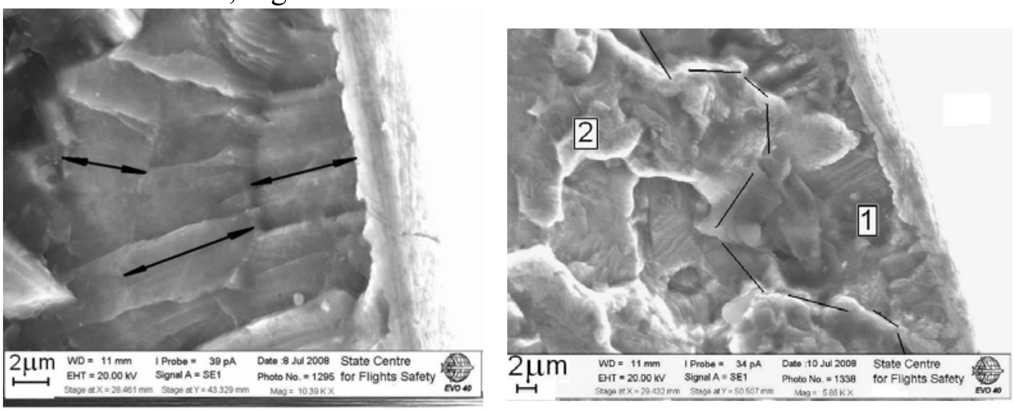


Figure 3. Overviews (a) of the failed disk of the first stage of LPC of engine D-30KU-154 and (b) its fracture surface. Arrows specify distances between macro-beach-marks of fatigue failure.

The initial fracture surface zone of the disk is along an external surface of the groove for the blade dovetail, Fig. 4.



a) b)

Figure 4. The fragment (a) of the disk fracture surface at the surface of the groove for blade with “streamlet-like” relief and meso-beach-marks, and (b) fracture area of transition from the “streamlet-like” relief "1" to facetted pattern (2). Arrows specify distances between MBMs.

The specified zone has been generated because of formation of several origins. The fracture surface analysis has shown that the main fatigue fracture has passed by this initial site. Therefore, it is necessary to consider this center as initial fracture with the crack propagation in small depth, but this initial crack has not defined general disk fracture. The fracture zone on the considered area has generated in result of transgranular, quasi-brittle material fracture by the sliding planes. The fracture surface patten is “streamlet-like” reflecting high frequency of material cyclic loading and its cracking in the HCF regime at durability more than 10^7 cycles.

On the considered areas which depth is within the limits of 50 microns, are revealed, also, MBMs of the fatigue fracture surface, characterizing borders for crack increment in one FC between them. On the observable fracture surface morphology it is seen such 4 MBMs, and there are blocks of fatigue striations, which spacing makes about 0.1 microns (see Fig. 4) are observed on the fracture surface after the “streamlet-like” relief. Fatigue striations orientation shows that they are created from the vibrating loading generated from the blade, or the disk fluctuations, as well as an initial zone.

On separate areas, along the initial fracture zone at the surface of the disk groove for blade, there have revealed drastically transition to transgranular cleavage of globules without the block of fatigue striations, Fig. 4b.

On the distance from the fracture origins, the crack development accompanied by formation of alternating areas of facetted pattern, cleavage of globules, and blocks of fatigue striations, which have created, as well as in the case of disks fracture on the rim parts that described above, in the previous section.

In area of MABMs there are dominates facetted pattern of the fracture surface. In local fracture zones, at this stage of the disk cracking, formed badly seen dimples. This entire pattern specifies fast development of the crack under hold time of disk loading when there are fluctuations of the disk can accelerate crack propagation.

The fracture surface morphology allows asserting for the disk operating time about 18000 hours that fracture from the surface of the disk groove for blade is realized at quantity of individual cycles up to 10^8. In this case, material fracture can be considered as realized in the VHCF regime [3]. This conclusion based on revealed fracture surface relief at the surface of the disk groove for blade (see Fig.4). There is the fracture surface relief in origins as the “streamlet-let” (transgranular, quasi-cleavage) that correlates with fractures at an operating time more than 10^7 cycles.

In connection with the revealed regularities of the crack path in the disk, the numerical analysis of its stress-state in the rim parts has been lead.

Stress-state of the disk

Stess-state distributions of the disk was analysed to comparer stress levels in different areas of the rim parts [4]. It has discovered that the maximum stress level along the disk circle takes place in area of the rim where air stream goes in, Fig.5. In fact, the area of the in-service crack initiation, where air stream goes out of the rim has on 50 MPa less stress level than area with maximum stress-state has that illustrated Fig.5c, d. The same situation takes place for the nominal stresses in the compered areas.

The discovered stress-state of the disk shows that the crack initiation placed in area with less stress-state for LCF regime than has area, which used for estimation of in-service disk durability during its design. It is evidently contradiction between stress-state and durability estimation for the disk failure in LCF regime, it should be crack initiation in another area, with realized in sevice failure.

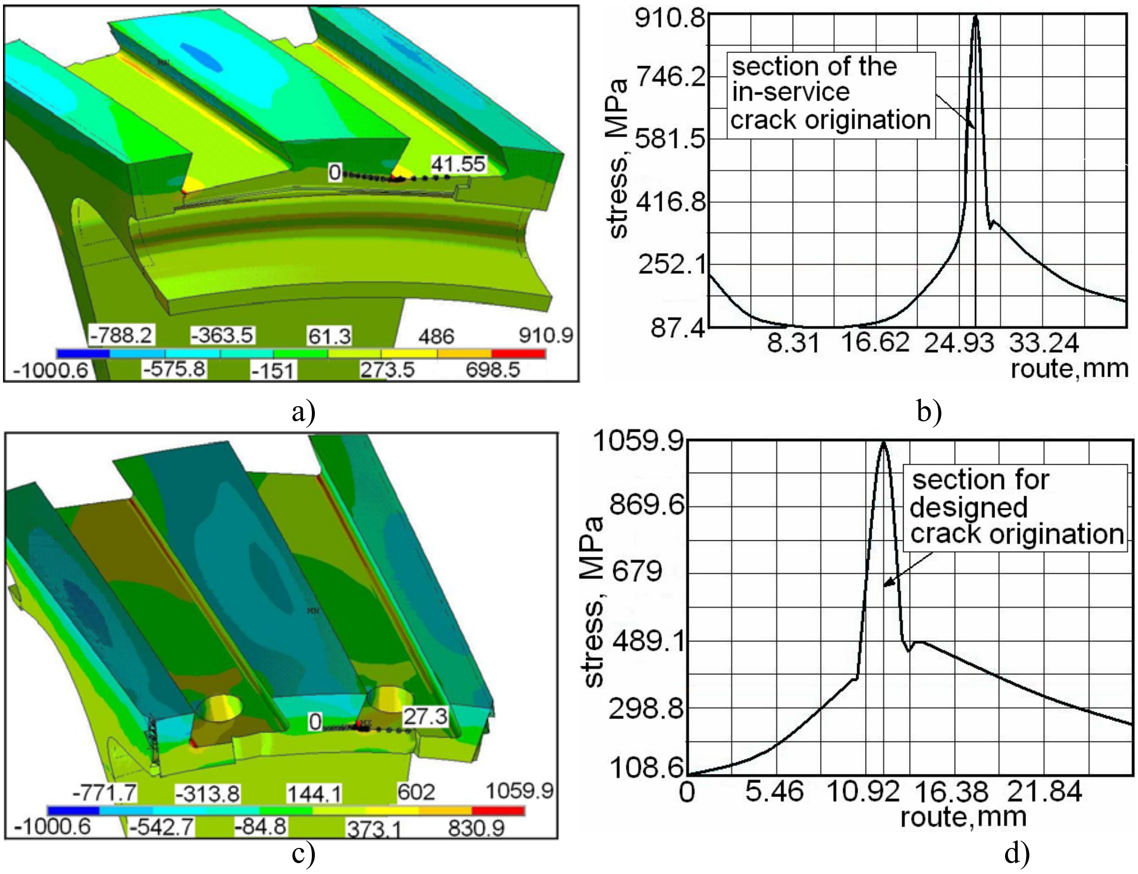


Figure 5. Overview of the stress distribution in rim area wih indicating stress level for the rim side (a) where air stream goes in and (c) out and (b), (d) stress dependence on the route in the direction shown in (a), (c) for the same rim area respectively.

DISCUSSION

Based on the performed fracture surface analysis of disks and results of numerical estimations of disk-rim stress-state it is possible to conclude that fatigue failures have not connected to a high level of maximum stress for designed in-service operation conditions but crack initiation mechanism corresponds to HCF regime for not less than 10^7 individual cycles. At the initial stage of fracture, the main role in crack development played cyclic loads of low amplitudes. Then, in the process of the crack propagation, there is a reduction of the disk stress-state. Cyclic loading caused low frequency of disk fluctuations, which caused crack development with formation of the block of fatigue striations and facetted pattern of fracture surface. Nevertheless, at an estimation of the crack growth period it is necessary to take into account that discussed fracture surface patterns should be related to the individual cycles of loading based on their know frequency. They cannot be considered as characteristic of disk loading in one flight.

There are bases to believe what exactly the mode of engine D-30Ku revolutions up leads to MAMB formation. Such statement follows from the realized failure of the disk. It has taken place at run on aircraft by the runway before take off that is connected to transition to more intensive mode of disk operation. The distance between MABMs reflects of the disk fatigue failure during one FC. However, there was not expressed dependence of the distance between MABMs on the crack length. The analysis of the last of 23 flights duration for the aircraft has shown that the engine operation duration had the period from 1.1 until 6 hours. The crack in-flight increment is the more for the disk longer time under loading. Last several flights had not regularities in duration from one flight to another that is why in the fracture surface at last stage of the crack growth there is not revealed natural increase of distance between MABMs in the direction of the crack growth (see Fig. 3). Summarizing estimations of crack growth duration in the disk, it is seen about 27 FC based on actual flights duration by the given aircraft.

CONCLUSION

Local of in-service disks failure in one section by the rim parts, not having supports on other sections is connected to a combination of mechanisms HCF and LCF.

Origin of fatigue cracks occurs under cyclic loading initially because of high frequency of blades vibrations and low-frequency fluctuations of disks, and the main crack development occurs because of the disk fluctuations.

In some cases, the disk material shows sensitivity to in-service cyclic loading that expressed in formation of dominant quasi-brittle facetted pattern of fracture surface.

Crack growth period in disk rim parts can make some tens FC and, in particular, for the investigated disk of I stage LPC of the engine D-30Ku-154 has made about 27 FC in accordance with actual duration of the airplane flights.

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