Very-High-Cycle-Fatigue Regime of In-service Titanium Blades Subjected to Multiaxial Loading During Aircraft Accessory Power Plant Operations

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ABSTRACT. *Nature of fatigue crack origination in engine TA12-60 fan-disk of VT8 titanium alloy has been considered. It was shown that crack origination takes place subsurface in Very-high-Cycle-Fatigue regime by facets which have not evidence in "Mo". Experimental results attested they-self that disk blades experienced resonance vibrations in the range of frequency from the acting air stream with multiaxial tension-bending-torsion cyclic loading. It creates enough stress level for blades failure in the design service goal at the durability 10^9 – 10^{10}cycles.he first section of the paper is to be a short single paragraph abstract outlining the aims, scope and conclusions of the paper.*

INTRODUCTION

Fatigue fracture process in metals usually taken into consideration applicably to different scale levels: micro- or nano- (Very-High-Cycle-Fatigue or VHCF-regime), meso- (High-Cycle-Fatigue or HCF-regime), and macro-scale level (Low-Cycle-Fatigue or LCF-regime) [1] - [4]. Transitions from one to another scale levels strongly expressed in accordance with introduced bifurcation diagram for metals [1, 3]. Applicably to titanium compressor disks there is in-service fatigue cracking taken place in LCF regime [5]. Contrary, titanium compressor blades have in-service fatigue cracking in HCF or VHCF regime. Therefore for these two type of structures different criteria used for estimating their critical in-service lifetime.

Aircraft blades in-flight subjected to bending-torsion-tension complicated external loading which directed to influence of their stress-state in dependence on the engine rotor speed. Blades can have experience of resonance by the one of the main loading axis (cyclic torsion or bending). Main designer idea is to exclude for blades in-flight possible resonance during long time operation engines.

Contemporary technology, introduced for new generation of engine structures, directed to possibility manufacture titanium disk and their blades as one structure. For example, this technology was performed for engine TA12-60 fan which in-service rare fatigue cracking taken place before design service goal. It is clear that the question grows up: what kind of criterion have to be used for estimating of this complicated structure in-service possible lifetime before its fatigue cracking.

Below this problem was considered applicably to titanium fans manufactured from VT8 (Ti-6Al-3Mo) alloy of aircraft engine TA12-60 being of "Accessory Power Plant" with design service goal 1000 hours.

TESTS PROCEDURE

Material and specimens

One of the in-service cracked titanium fans of the engine № 3460214363 was used in the present investigation with in-service time 435.33 hours. View of the failed disk is presented in Fig. 1.

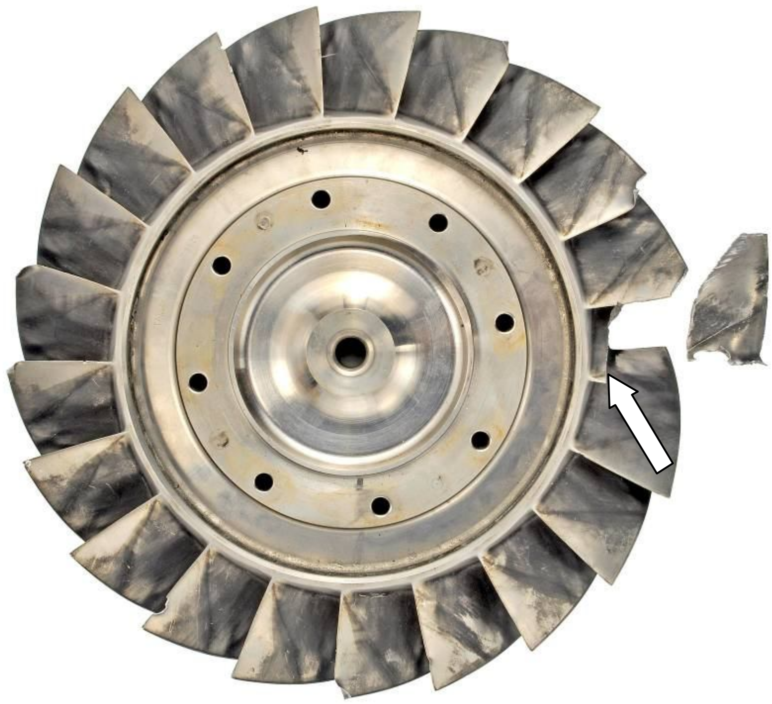


Figure 1. View of the in-service fatigued titanium fan disk TA12.001.032.08 № 103020 with failed blade. White arrow pointed out area of crack propagation.

First, round bar specimens were manufactured from fan-disk and standard tension tests were performed for estimating material mechanical properties. It was shown that the mechanical properties are in accordance with certificate given for manufactured fan material that presented Table 1.

Table 1. Mechanical properties

nn	Ultimate stress R_m (MPa)	**δ,** %	**Ψ,** %
1	1060	16	28
2	1050	16	27
3	1050	16	26
4	1050	18	29
Certificate for fan №06814R09	104,4	15,6	44,3
Standard 90197-89	98-118	≥10	≥25

Second, quantitative spectroscopic analysis was performed applicably to different areas of the investigated fan-disk. Spectrometer QSG750 of the OBLF-firm was used in this case. It was shown that fan has been manufactured from the VT8 titanium alloy in accordance with certificate given for manufactured fan that presented Table 2.

Table 2. Chemical composition (in %) of the fan-disk complicated structure of VT8 titanium alloy. “Ti” is remainder.

Specimen	**Al**	**Mo**	**Si**	**Fe**	**C**	**O**	**N**	**H**	**Sn**
Standard 90013-81	5.8-7.0	2.8-3.8	0.20-0.40	≤0.30	≤0.10	≤0.15	≤0.05	≤0.015	≤0.4
Certificate №06814R09	6.67	3.50	0.36	0.049	0.008	0.102	0.003	0.002	0.11
Part of separated blade	6.16	3.35	0.35	0.07	0.03	–	–	–	–
Fan-disk	6.0	3.0	0.35	0.075	0.04	–	–	–	–

Third, metallographic analyses were performed to estimate material structure. In accordance with certificate material has to be two-phases ($\alpha+\beta$) with dominantly globular shape of α–phase of “16” level by the standard 90197-89. It was shown that material structure is in accordance with certificate.

Results of all tests have shown that titanium alloy VT8 of the investigated fan-disk has mechanical properties, two-phase structure, and chemical composition in accordance with order of certificate given by manufacturer and in accordance with order of standards.

Fractographic and X-ray analyses

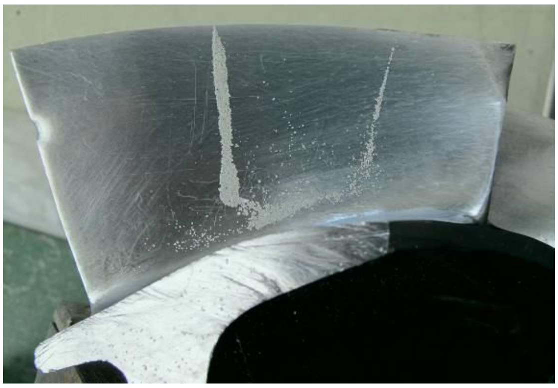
Fracture surface of failed fan-disk was investigated on the scanning electron microscope of Karl Zeiss with using special device “Inca” for local spectroscopic estimation material composition. It was considered material composition by the fracture surface, and by the section prepared in the perpendicular direction to the fracture surface in area of crack origination.

Blades resonance monitoring

A segment of fan-disk with three blades was prepared for estimating blades resonance characteristics in the range of 500-20000 Hz. Blades were polished by the concave surface. This segment was fixed in a special facility by the rim plane.

Piezoelectric oscillator was used for influencing in the segment one of the blades vibration from the metallic needle. On the small distance from the vibrating blade was placed detector which had not contact with the tested blade during registration the blade frequency.

On the blade concave surface was placed sand to register area with its high density under different influenced external frequency as it reproduced in Fig.2. It was discovered for this type of blades many simultaneously appeared resonances in the investigated range of external frequencies.



a)

b)

c)

d)

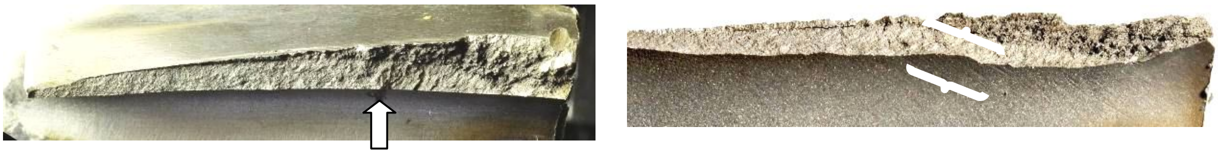
Figure 2. Types (a) - (d) of complicated resonances by the three simultaneously different forms for the same blade but for various influencing of external frequency.

RESULTS OF INVESTIGATION

Fractographic analyses have shown in area of crack origination the fracture surface plane of cracked material offset from the main plane (indicated by unlabeled bracket) as is reproduced in Fig.3.

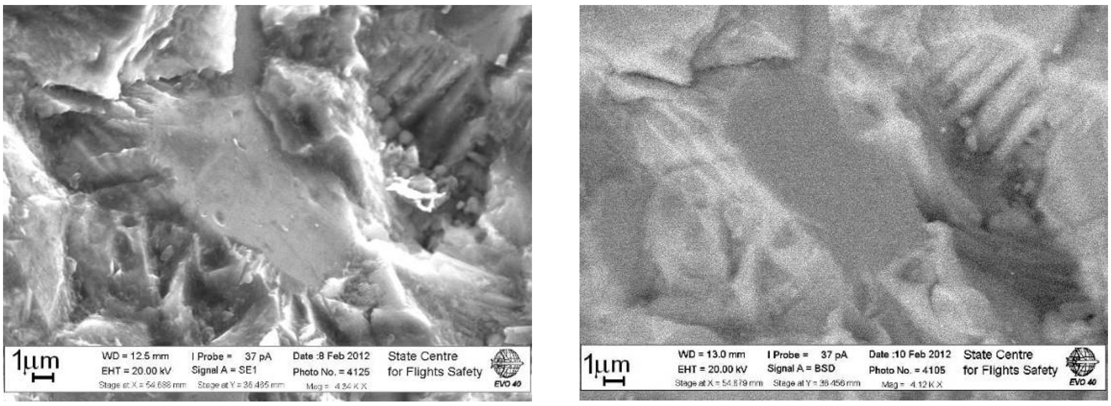
Crack origin area located in some distance from the concave surface as is reproduced in Fig. 4. The origin area has multiple smooth facets in the border of metal cracking through the α–phase.

Material chemical composition by the all smooth facets of cracked α–phase was analyzed with using X-ray spectroscopy. In all facets there were not discovered "Mo", Fig. 5. In neighbored β-phases there were discovered "Mo" in the accordance with certificate and standard (see Table 2). These data were compared in the slice plane prepared in the perpendicular direction through the area of origin not far from the concave surface.



a) b)

Figure 3. The fatigued blade fracture surface (a) face and (b) looking slightly up of this surface with evidence of viewed shape of the border by the concave surface in area of crack origination. Crack origination area indicated arrow and unlabeled bracket.



a) b)

Figure 4. View one of the smooth facets in area of subsurface crack origination (a) in the secondary electron and (b) in the back scatter regime.

It was discovered the same material composition directly in area of crack origination: no evidence of "Mo" in α–phases and β-phases. On the distance more than 0.1 mm there was discovered “Mo” in both phases in accordance with certificate and standard (see Table 2).

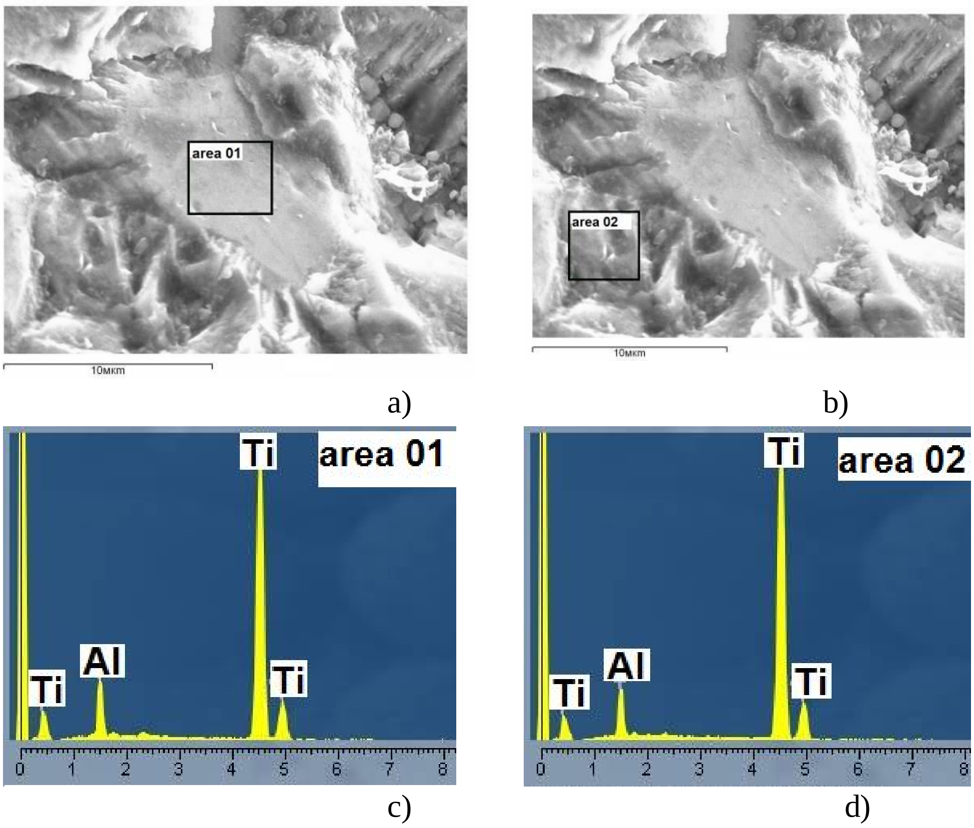


Fig. 5 Fracture surface (a), (b) in one of the origin and (c), (d) chemical composion in areas “01” and “02” of this origin without evidens of “Mo”.

Consequently, in the blade fatigue crack origination has taken place, first, in α-phases subsurface where material has not evidence of «Mo».

The blade of designed shape (large chord) has different types of resonance as was discovered during performed investigation. In some rare cases there was only one type of resonance with blade bending. But in many cases there were two and three neighbored resonance by the bending and torsion Modes (see Fig. 2). In other cases there were discovered not depended blades vibrations by two forms. For example, there is can be simultaneously large vibration with less bending stiffness for one part of blade but in another blade part there is another Mode of vibration with more intensive torsional stiffness. It can be seen gradually transition from one type of resonance to another. Therefore, material subjected to multiaxial in-flight loading with simultaneously tension (because of disk rotation), bending and torsion. It can be seen that one of the resonance, for example, is reproduced in Fig. 2, takes place in area of crack origination. The minimum frequency for the blade bending resonance in area of crack origination related to 1950 Hz.

Consequently, fatigue crack of the blade took place in service subsurface in area of material without or very less percent of “Mo” under possible resonance under multiaxial cyclic loading (bending and torsion).

DISCUSION

Discovered subsurface material cracking in the blade of VT8 titanium alloy is typical case for of VHCF. The same features of subsurface crack origination were earlier considered in VHCF regime with specimens test under frequency 20 kHz for titanium alloy VT3-1 of the same system Ti-6Al-3Mo but having “Cr” [5]. Smooth facets by the α-phases fatigue cracking were performed in the globular $(\alpha+\beta)$ two-phase structure. There was not revealed “Mo” by the smooth facets in area of crack origination. Therefore, it is titanium alloy chemical inhomogeneity that influenced fatigue in VHCF regime.

But in the case of specimens uniaxial tension-compression of VT3-1 titanium alloy there was minimum stress level 350MPa when cracking took place subsurface at $5x10^9$ cycles. That is why it is not only chemical inhomogeneity that influenced subsurface crack origination in VHCF regime.

In the discussed case, the blade fatigue cracking of VT8 titanium alloy was appeared at 435.33 hours since the disk was new. Operating period for the fan-disk with blades under the resonance, if will be considered minimum frequency of 1950 Hz, is $3600x1950x435.33 = 3.06x10^9$ cycles.

In flight the blade experienced influence of the air-stream with frequency by the fourth and fifth blades harmonic respectively in the range of (1599-1664) Hz and (1998-2080) Hz. Measurements accuracy has not less than 2% for estimated blade resonance and air-stream frequency. Consequently, there can take place resonance for blades with different frequency but not only in the case of one resonance.

Performed investigations have shown that in blades can be realized different types of complicated multiaxial loading with independent vibration by the bending and torsion Modes (see Fig.2).

It is clear that at the in-service time 453.33 hours there will be random resonance in blades under multiaxial cyclic loads with frequency more that minimum 1950 Hz. Various fan-disk operations will have more or less intensive influence on the blades damage accumulation. It is especially evident that there was revealed situation with transition from one to another resonance frequency without small interval without resonance. Different blades in fan-disk have various weight and geometry in the range of standard that influenced difference in resonance frequency and possibility to realize more or less complicated case of resonance. In the case of multiaxial resonance with highest stress level there will be only one blade that experienced this influence up to fatigue cracking in the design service goal 1000 hours. In one case it can be critical state before 1000 hours (or less than 1010 cycles), but for many blades it can be in-service time more than 1000 hours (or more than 1010 cycles). That is why in service there were very rear cases of blades fatigue cracking, and for one fan-disk only one blade had failure.

Consequently, in-service blades fatigue cracking take place under resonance in the case of multiaxial loading. Their in-service time before fatigue cracking depended on the type of resonance and in the realized operating condition for fan-disk can be seen since they were new up to critical state at 400 hours and less.

CONCLUSION

1. Fan-disk blades of engine TA12-60 have appearance in VHCF regime because of resonance by the different Modes of multiaxial cyclic loading.
2. Manufacturing procedure titanium alloys of Ti-6Al-4Mo system influenced the blades cracking in VHCF regime because of in material there can be chemical inhomogeneity without (or with minimal value) of "Mo" in the α–phase. It influenced material local stress-state and promotes durability decreasing in VHCF regime.
3. Large chord blades of fan-disks can experienced various form of vibrations by the different simultaneously acting independent Modes when one of them can be resonant. During engine operation one resonance form can have gradual transition to another form with another frequency under influenced air-stream.

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