Fatigue cracking in bifurcation area of titanium alloy at 20 kHz

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ABSTRACT. *The problem of turbine disk fatigue failure and blades damage coming from practice show a special mechanism of fracture which is not similar with fracture due to low cycle fatigue (LCF) or high cycle fatigue (HCF). In-service data give a reason to assume, that cracking of turbojet elements has an additional mode of loading. This is a vibration with small amplitude and high frequency, which led to a very high number of loading cycles (gigacycle fatigue). In order to study the features of crack origination, crack path and fatigue resistance of titanium alloy in gigacycle regime, ultrasonic fatigue tests were carried out. Three different characteristic types of initiation mechanisms which could involved additional mode of fracture in gigacycle regime were observed.*

INTRODUCTION

One of the main task for providing safety flights is linked with the problem of understanding crack growth processes in propulsion systems of aircrafts like turbojet engines. The safety of such constructions is a very important subject. Indeed, reaching a critical condition in one element inside a turbojet engine could lead to break the propulsion system or aircraft on the whole. Therefore, monitoring cracks and predicting parameters of crack path in aviation materials are very important problems. Generally, the control of safety condition of aircraft elements during operating conditions is carrying out by the determination of cracks occurrence. These controls are not carried out before each flight and by this way an understanding of damage accumulation mechanisms in material due to operating conditions is required. Moreover, the determination of drive parameters for fatigue crack initiation and propagation processes is very important to predict the crack growth. In case of turbojet engine disks, which are made in titanium alloy, fatigue damage accumulation could be assumed based on several fatigue mechanisms. In order to predict a safe fatigue life for disks, damage accumulation models based on LCF and HCF mechanisms or combination of them are generally used. According to the in-service data for hubs of disks, the main mechanism of fatigue damage is LCF. But in case of the ring part of the turbojet engine disk, cracks generally occur in the region of blade's fixing, where high frequency vibration could have an influence on fatigue damage accumulation. Mechanisms of LCF and HCF do not take into account the effect of high frequency vibrations. For blades the frequency of vibration could reach 4420-4520 Hz [1]. Therefore, after 700-800 hours of exploitation the blade could reach 10^{10} cycles. This is typically a region of VHCF or gigacycle fatigue [2].

TEST PROCEDURE

Nowadays, fatigue properties of titanium alloys in VHCF is not well studied, because of difficulties in getting experimental data by using conventional testing techniques. In order to study the fatigue behavior of titanium alloy VT3-1 in VHCF regime, 21 smooth specimens with a corset shape (smaller diameter of cross section is 3 mm) were machined from the ring part of a turbojet engine disk. This is the location of the disk where vibrations occur actually. Chemical composition of the tested material is presented in Table 1.

Table 1. Chemical composition of titanium alloy VT3-1, weight %

Fe	C	Si	Cr	Mo	N	Ti	Al	Zr	O	H
0.2-0.7	< 0.1	0.15-0.4	0.8-2	2-3	< 0.05	85.95-91.05	5.5-7	< 0.5	< 0.5	< 0.015

Specimens were machined from the disk of a turbojet engine compressor. This disk was in exploitation for 8000 hours on a real aircraft. According to a state standardization it is a regular durability for such elements. Technical control did not find any defects in the material due to in service time. Cylindrical billets were cut from the ring part of the disk by electro-erosion method and then used for machining specimens. Figure 1 shows the overview of the disk and the location of these billets in it.

According to the data from literature for titanium alloys [3] the stress level for present investigation on fatigue strength was chosen in the range 40-45% of the ultimate tension stress (UTS). For wrought titanium alloy VT3-1 the UTS is varying from 930 to 1230 MPa [4], depending on the thermal treatment and type of production blank (bar, die and so on). In order to study the fatigue properties in the gigacycle fatigue regime, the lower prediction value for the fatigue limit was chosen as lower border of stress level for the present fatigue tests. A series of 21 specimens was tested under several stress amplitudes from 370 to 430 MPa. All fatigue tests were carried out at room temperature, in air, under fully reversed tension (R= -1) on a piezoelectric fatigue testing system at a loading frequency of 20 kHz. The testing machine was operating continuously (with no pulse). Its servo-control system realizes both no overload and a permanent control of the displacement amplitude.


Figure 1: Location of specimens in the turbojet engine disk.

From the technological point of view the main idea of piezoelectric fatigue system is to transform a high frequency sinusoidal electric signal into mechanical vibrations with a same frequency. This scheme of activating vibrations gives a possibility to control fatigue test by computer [2]. In order to avoid self-heating of the specimen due to vibrations at high frequency, special cooling air-gun was used. Flow of cooling air keeps a stable temperature during the test. Pyrometer temperature measurements show a surface temperature of the specimen of 18-20 °C.

EXPERIMENTAL RESULTS

SN curve

The results of fatigue tests are shown on Figure 2. It is clear, that the S-N curve for titanium alloy VT3-1 shows a permanent decreasing of the fatigue strength. There is not a horizontal asymptote. Such fatigue behaviour of titanium alloy in gigacycle regime is similar with a lot of fatigue tests results on steels and cast iron [5]. In case of titanium alloy, the difference in fatigue limit at 10^7 and 10^{10} reaches 45 MPa. Moreover, experimental fatigue life in this region has a big scatter. For example, under the stress amplitude 385 MPa one specimen was cracked at 1.01x10^7 cycles, second-one at 2.5x10^8, third-one at 1.4x10^9 and last-one at 1.006x10^{10} cycles. For another stress level between 370 and 415 MPa, the scatter is high too. With increasing the stress level above 415 MPa, failures of specimens mainly occur before 10^7 cycles. Big scatter of experimental data in the stress range from 370 MPa to 415 MPa is the base for assuming, that the fatigue behaviour of titanium alloy VT3-1 is not uniquely determined. It means that at one stress amplitude, the fatigue life time could vary in a wide interval (up to 3 magnitude orders). This is not a classic case, strong determinate (within the scatter) behaviour of material. This is a special area, which could be named “bifurcation area”, with a non-classic law of fatigue life. By this way, so large scatter of fatigue life could be explained by the existence of different defects or features of the material's micro-structure. Such defects could lead to the specimen failure at different durability under the same load conditions.

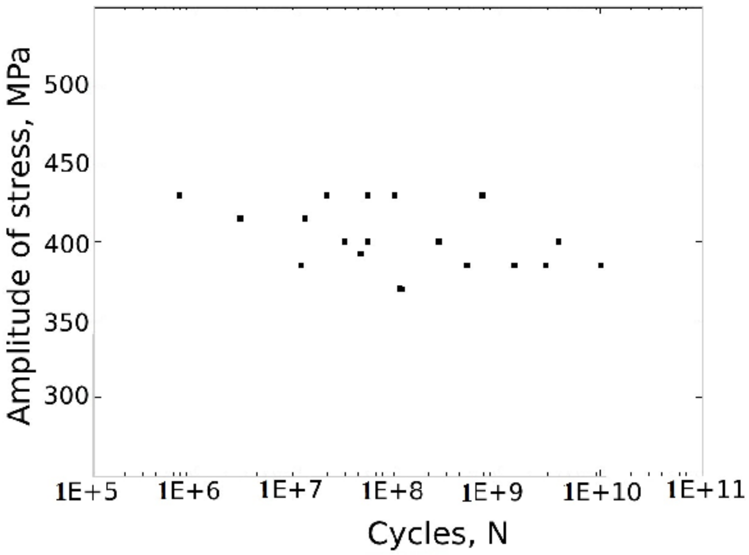


Figure 2: SN-curve for titanium alloy VT3-1 smooth specimens under fully reversed tension

SEM observations

In order to study the reason of so big difference in durability and to try to correlate this with a position and shape of the crack initiation zone, SEM observations of the specimen fracture surfaces were carried out. Some specimens have a surface crack initiation, but most of the specimens have a crack origination zone located in the bulk of material. Investigation of internal initiation area showed a difference in its geometry and position. Based on fractography analysis three general types of crack origination zone could be defined in the VT3-1 titanium alloy under fully reversed tension.

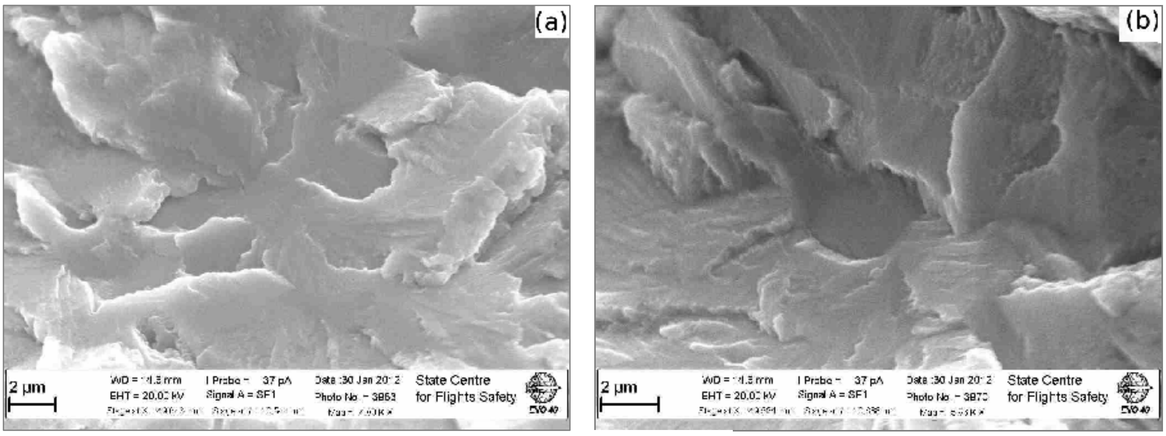


Figure 3: Crack initiation (a),(b) in two locations from the “smooth facet”

Type one is crack initiation from the ‘smooth facet’ (Fig. 3). This type of crack initiation zone is the most common one for titanium alloy. If the material has not strong micro-structural deviations or defects, crack starts very often from this kind of formations in gigacycle fatigue. For some specimens it was discovered, that several smooth facets could be formed in different areas of the fracture surface in the same time, but finally only one facet determines the main crack. The smooth facet could be located as in deepening of fracture relief and could be bordered by almost vertical “walls”, as in the local top of relief (Fig. 3b).

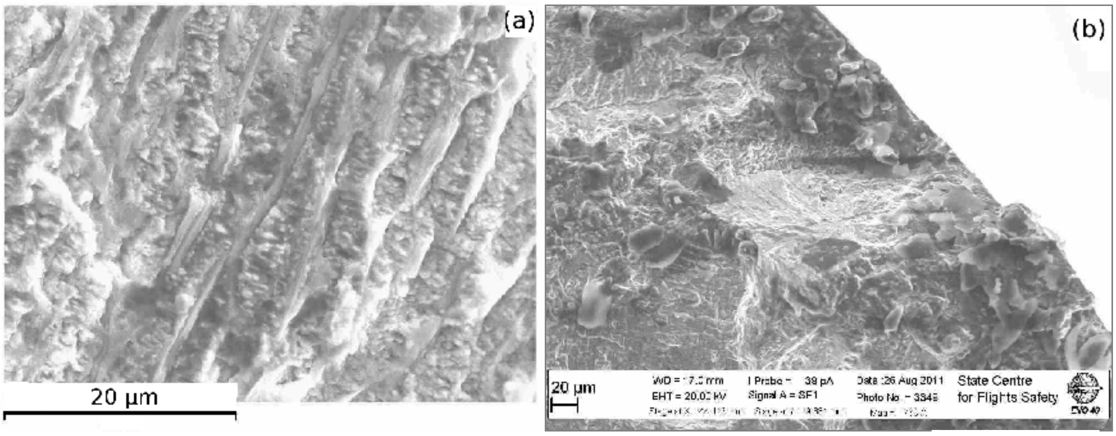


Figure 4: Two examples (on two specimens) of structural irregularities in the area of crack origination due to the production process.

Type two is cracking due to strong structural irregularities in the microstructure, which occurred due to the production process such as a thermal treatment, cooling conditions and others. Figure 4a shows an example of strong irregularity of the microstructure. This is a system of parallel laminar layers, with high concentration of alpha stabilizing elements in it. On figure 4b another type of structural formation is presented. This shows traces of brittle fracture. It has to be noticed that the chemical composition of this formation is deviated from the normal material (see Al and Mo content Fig.5b and Table 1)

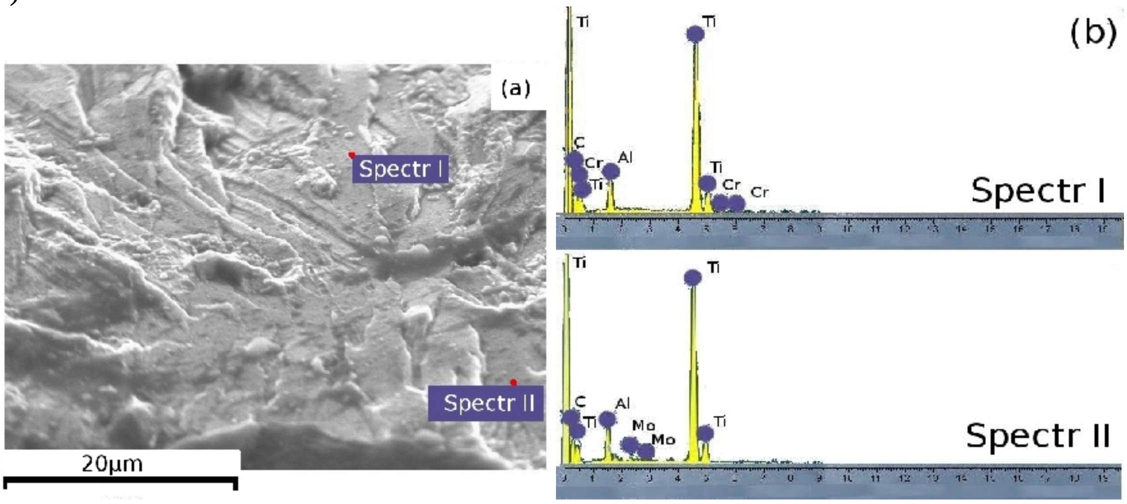


Figure 5: View (a) of crack initiation area (the same as shown in Fig. 4b) and (b) chemical composition of “pseudo-inclusion” in this area.

Type three is a cracking from features of the microstructure formation as a super-grain. Super-grain could accumulate fatigue damage: (i) along the border of grains (Fig. 6a), (ii) inside the super grain formation (Fig. 6b).

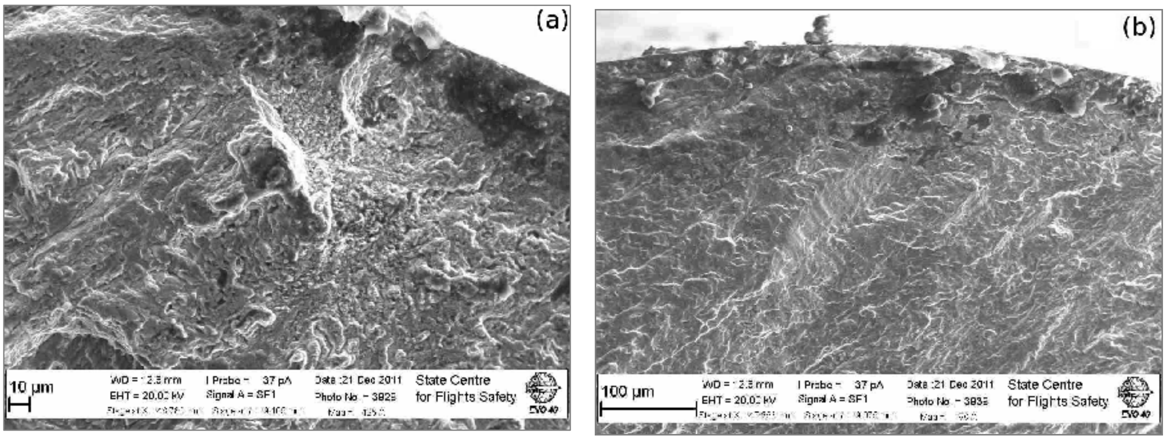


Figure 6: Fracture from super grain formation.

DISCUSSION

Experimental results shows that there could be two principal crack initiation positions. First type is a surface crack. Fatigue results on titanium alloy VT3-1 in the range of 370 – 430 MPa have provided 3 specimens (between 21) with surface cracks. Most of the fatigued specimens have an internal crack. These results are in good agreement with bimodal distribution of the fatigue life [6]. According to this assumption, data for surface and subsurface crack origination could be described separately by two individual distributions. Generally, each distribution could have its own law of fatigue life (Fig. 7). Left branch of this complex SN-curve is related with mechanisms of crack origination from the surface. With decreasing stress level, crack origination position has a transition from surface to subsurface. Some authors pointed out this area as a region with 'competition' between Mode 'A' (surface crack initiation) and Mode 'B' (subsurface crack initiation) [7]. Transition area is characterised by big scatter of fatigue life. Below region of 'competition' the major part of the results shows subsurface cracks.

In order to describe the process of transition, two probabilities of failure should be taken into account p_1 and p_2. Probability p_1 is related with the mechanism of surface crack initiation. With regards to experimental data, in the range of high stress levels the probability p_1 has a maximum. With decreasing stress level it goes down and has a minimum at low stress. In opposite, the probability of failure with an internal crack origination, p_2, has a minimum at high stress levels, and permanent increasing with decreasing of stress level. This concept describes a distribution of crack origination location in terms of failure’s probability. At the same stress level in the transition area we can find some specimens with surface cracks, and others with internal crack, but, for example, under lower stress levels, more often crack appears in the bulk of the material.

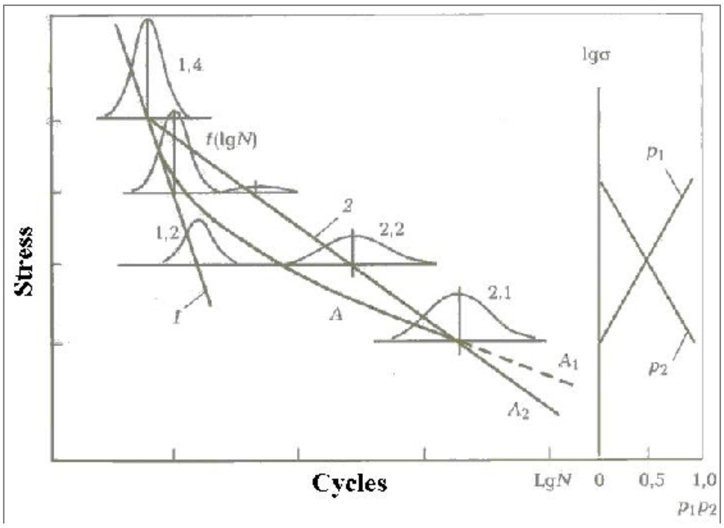
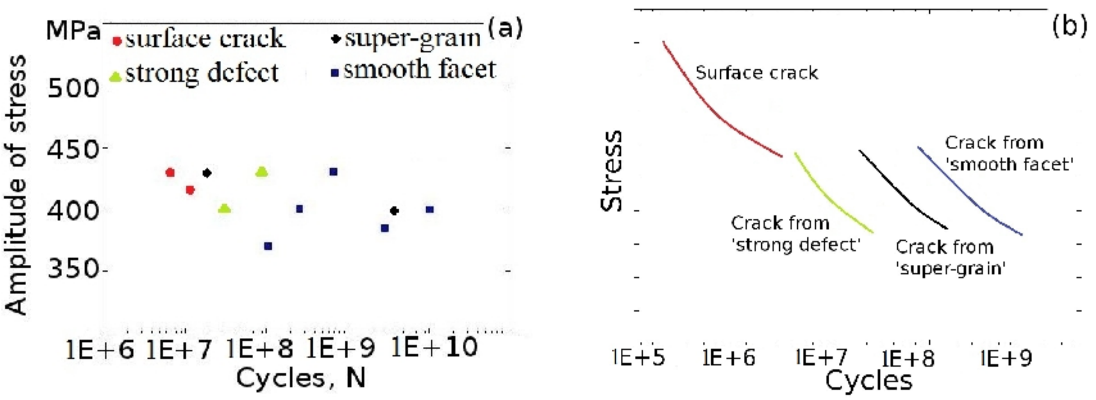


Figure 7: Bimodal fatigue life distribution in bifurcation area for metals with difference in probability p_1 and p_2 for one of the acting fracture mechanisms.

In case of titanium alloy VT3-1 experimental data under low stress levels also have a big scatter. There is no strong competition between surface and subsurface mechanisms of cracking. In order to understand is there any 'competition' between mechanisms for subsurface cracks or not, SEM observations of crack origination area were done. Results of observations have shown, that crack initiation zone could have several different types related with the microstructure. Sometimes, the crack occurs from strong defects of microstructure, such as system of laminar layers with a high concentration of alpha-stabilizing elements. Another defect of microstructure is a formation of volume in material with a higher concentration of aluminium and, therefore, higher hardness. So, effect of such area reminds inclusion, but it is not a real inclusion. Generally, the fracture surface of such element is almost brittle, that proved hypotheses about higher hardness. Next discovered formation of micro-structure is 'super grain'. These formations have the same chemical composition with normal titanium alloy. Only one difference is the size of zone with mostly the same orientation of sub-grains. This type of structural singularity could be also a crack initiation factor during gigacycle fatigue. It should be pointed out, that from technological point of view it is impossible to avoid singularities of microstructure in big components like turbojet engine disks. Therefore, probabilities of failure from one of discovered defects always exist for metals. It can be done some systematization of fatigue data inside this not-stable area by introducing multi-modal distribution of fatigue life. According with our data, specimens with a smooth facet as crack initiation factor have a longer fatigue life. Specimens with strong structural irregularities have a shorter fatigue life. The role of super-grain is not clear enough because of limited cases in our experimental data with such formation. Based on our first results (Fig. 8a) and assuming, that materials with bigger grains have a lower fatigue resistance, fatigue life of specimens with super-grain formation should be in region between data for 'strong defects' and 'smooth facet'. Sketch of multi-modal distribution is given on fig.8b.



. Fig.8. Experimental data (a) and sketch (b) of multi modal distribution for fatigue life

CONCLUSION

(1)The fatigue strength of titanium alloy VT3-1 from 10^7 and 10^{10} cycles is permanent decrease. Difference of fatigue strengths at 10^7 and 10^{10} cycles reaches 45 MPa. (2)Experimental fatigue life has a big scatter beyond 10^7 cycles. This scatter could be related with features of the material microstructure. Three main types of crack initiation factors were observed: strong defects of structure with chemical composition features, super grain formations and smooth facet formations. Generally, specimens with a strong defects of microstructure have a shorter fatigue life, compared with a case of smooth facet. Therefore, multi-modal fatigue life SN curve for subsurface crack could be proposed.

(3)Most of fatigued specimens in gigacycle regime had a subsurface crack, but some of them had a surface crack. Under one stress level these two mechanisms could exists, but the probability of failure from surface is decreasing with decreasing the stress level. These results are in good agreement with bimodal distribution of fatigue life.

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