Fatigue behavior of the titanium alloy Ti-6Al-4Mo in bifurcation area at 20 kHz

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Abstract. In order to study gigacycle fatigue strength of material for aviation industry, the titanium alloy Ti-6Al-4Mo was tested under stress levels in the range 370 – 430 MPa at frequency 20 kHz. Results of fatigue tests shows a big scatter in life beyond 10^7 cycles. In order to understand a nature of such fatigue behavior, an additional investigation on fracture surface of fatigued specimens was carried out by SEM. Three types of micro-structure irregularities and one general mechanism leads to crack nucleation were founded. Results shows that ~~F~~fatigue life related with a type of crack initiation formation.

Introduction

Titanium and titanium alloys are materials, which are widespread in modern industries, among others: chemical industry (elements of pumps), heavy engineering (elements of engine like connection rod), aviation (elements of turbojet engine like disks, blades). All these elements works under cyclic loading and that is why a problem of fatigue damage accumulation and fatigue cracking in titanium alloys is actual. In relation to aviation, blades and disks of turbojet engine are most susceptible to fatigue failures. In case of disks, the fatigue damage accumulation can be categorized in Low Cycle Fatigue for the hub part and in High Cycle Fatigue for the ring part of disks. For blades, the problem of vibrations is most actual. Engineering solutions to reduce the risk of blades fracture due to vibrations, is avoiding any vibration at the natural frequency of the blade [1]. Nevertheless, the normal operating conditions for such elements allow vibrations at frequencies of several kilohertz. Therefore, even if the blade vibrates at 1 kHz, it will reach 10^8 loading cycles after 28 hours. Consequently, during in service time some blades could get more than 10^{10} low amplitude loading cycles. This is a region of Very Hight Cycle Fatigue (VHCF) or gigacycle fatigue.

In spite of large practical interest of engineers in the fatigue behavior of materials under a high number of loading cycles, nowadays there is not enough experimental data. First of all the reason of this is related to the low efficiency of conventional fatigue testing methods in gigacycle regime. Point is that, cyclic loading under low frequency can not provide a regular tests beyond 10^8 cycles because of long time-consuming, large consumption of energy and, therefore, high price of such research. Moreover, very high amount of time makes that tests in gigacycle regime are not feasible with conventional fatigue testing systems. For example one test with an experimental base of 10^{10} cycles at 50 Hz take more than 6 years of non-stop operation. Results of fatigue tests beyond 10^{7} cycles at conventional tests frequency had shown, that metals could fail even if the stress amplitude is lower than the conventional 'fatigue limit' [2]. Very soon, the same results were obtained in the laboratory headed by Claude Bathias on an ultrasonic fatigue testing system [3].

Ultrasonic fatigue testing system provides an opportunity to carry out fatigue tests at 20 kHz. The main distinction of ultrasonic concept from conventional fatigue tests is using the natural frequency of the specimen for applying cyclic load. The main scheme of an ultrasonic fatigue testing system [4] is shown on Figure 1.

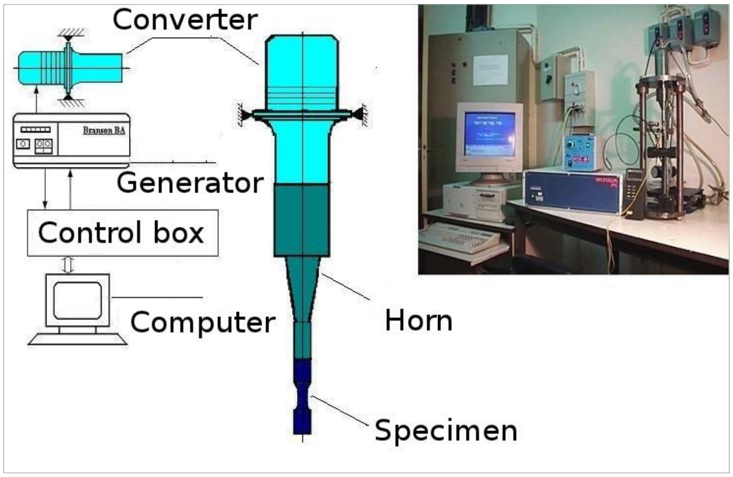
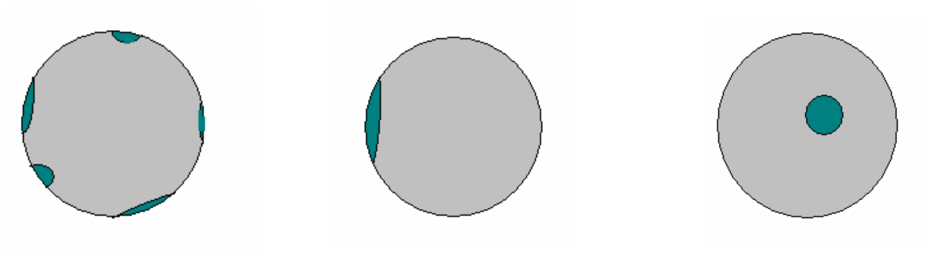


Fig. 1. Principal scheme of the ultrasonic fatigue testing system [4]

All parameters of fatigue test are generated and controlled by a special software. The drive signal from computer goes through a control box to the generator. Based on the in-box information, the generator produce a sinusoidal high frequency (20 kHz) electrical signal which goes to the piezoelectric converter. There, it is transformed to vibrations at the same frequency. Full system automatically adjusts on natural frequency of the specimen and during all the test-time works in resonance regime. As soon as the specimen is cracked, the software automatically stops the test procedure because of the specimen stiffness decreasing.

Thanks to using this ultrasonic system, an experimental base for fatigue tests can be built in the range of $10^{8} – 10^{10}$ cycles. In relation to modern technology and long life design, this range has a big practical interest. Moreover, results of fatigue tests at high number of cycles shows a transition in crack initiation mechanisms with increasing number of cycles [5]. Figure 2 represents a general regularity in locations of crack origination depending on the number of cycles.



$N_i=10^4$ cycles $N_i=10^6$ cycles $N_i=10^9$ cycles

Fig. 2. Location of the crack origination depend on number of cycles [5]

Big practical interest for experimental fatigue data in the gigacycle regime, lack of results on fatigue strength for Russian titanium alloys beyond 10^8 cycles, changing in crack origination mechanism and studying the features on fracture surface due to fatigue crack in VHCF regime are the areas of interest of the present work.

Test procedure

As noted before, nowadays, the problem of possible fatigue destruction in turbojet engine disks and blades is actual. Results of blades failure, coming from an operating conditions, may show subsurface location of crack origination which are typical of the gigacycle regime. In order to study the fatigue behavior of a titanium alloy in gigacycle regime, one of the most representative $\alpha-\beta$ titanium alloy was chosen: Ti-6Al-4Mo (VT3-1 according to the russian standard). Series of 21 smooth specimens with a corset shape were machined from the turbojet engine disk of a real aircraft. The disk was in-service for 8000 hours. According to state standardization it is a regular durability of this element. Note that technical control did not find any defects in the material due to exploitation. Drawing of the specimen and location of electro-erosion machining in the disk are shown on fig. 3.

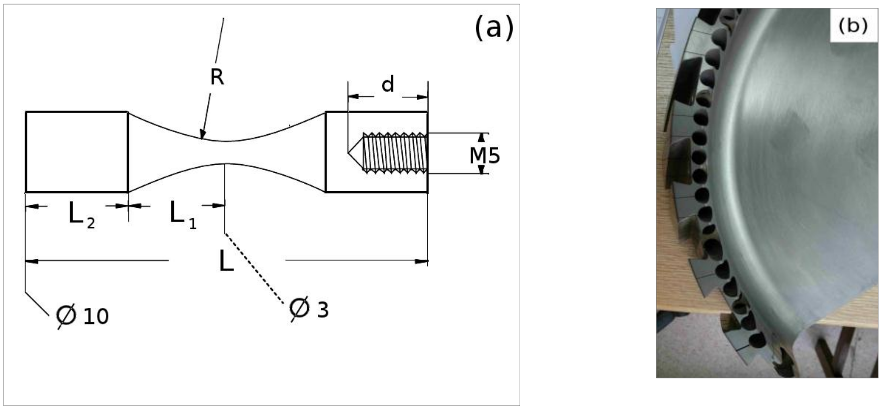


Fig. 3. (a) Drawing of the fatigue specimen and (b) location of machining in the disk.

Fatigue tests were carried out on a piezoelectric fatigue testing system (fig. 1) under fully reverse axial load (R=-1) at 20 kHz. During the test time, the working part of the specimen was permanently cooled by special air gun, in order to provide a test at room temperature and avoid any self-heating. In-situ pyrometer temperature measurement shows a surface temperature of the specimen between

18 and 20 °C. Stress levels for fatigue tests were chosen according to classical assessment of the fatigue strength in the range of 40-45 % of quasi-static ultimate tensile stress. Depending on the type of production (bar, sheet, die and others), the UTS for Ti-6Al-4Mo vary in the range of 930 – 1230 MPa [6]. Since the area of interest is the fatigue properties in gigacycle region, the lower range of prediction fatigue strength was chosen as a stress amplitude for tests. Therefore, fatigue test were carried out under stress levels from 370 to 430 MPa.

Experimental results

Experimental data for titanium alloy Ti-6Al-4Mo show a large scatter of the fatigue life beyond 10^7 cycles. At stress level ~~4~~385 MPa the scatter in fatigue life reach three magnitude orders (Fig. 4). With increasing stress amplitude, the scatter is strongly reduced and at stress level 415 – 430 MPa the results of fatigue tests are mostly grouped within $10^7 – 10^8$ cycles. With decreasing stress level, the scatter is increasing: at 370 MPa it reaches 3 magnitude orders. In order to clarify the reason of such fatigue behavior an additional methods of investigation was used. Fracture surfaces of fatigued specimens were observed by Scanning Electron Microscopy (SEM) and for several specimens a local spectral analysis and an observation in regime of back scatter electron was carried out.

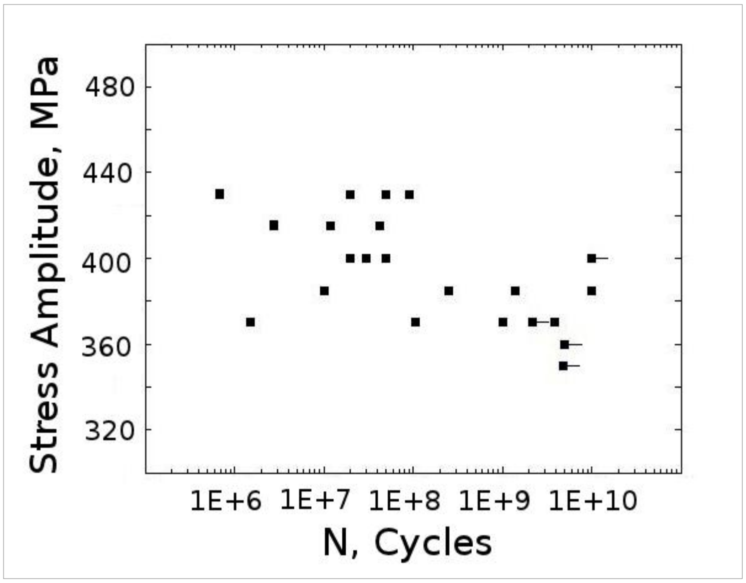


Fig. 4. Fatigue life of titanium alloy Ti-6Al-4Mo under fully reversed tension at 20 kHz.

As shown on Figure 4, S-N curve for titanium alloy Ti-6Al-4Mo (VT3-1) is permanently decreasing. The difference in fatigue strength between to 10^6 and 10^9 cycles reaches 60 MPa. Moreover, the location of crack initiation area has a transition from surface (for specimen under stress level 430 MPa, fatigue life 6.841×10^5) to subsurface (for specimen under stress level 370 MPa, fatigue life 1.06×10^8). It is worth noting, that almost all fatigued specimens in gigacycle regime have an internal position of crack origination. Therefore, the big difference in fatigue durability of specimens could be related with features of the microstructure of the titanium alloy. Observations of the micro-section by optical microscopy show variation of grain size. Clearly seen several areas with a fine-grained structure, surrounded by normal, representative microstructure, Fig. 5.

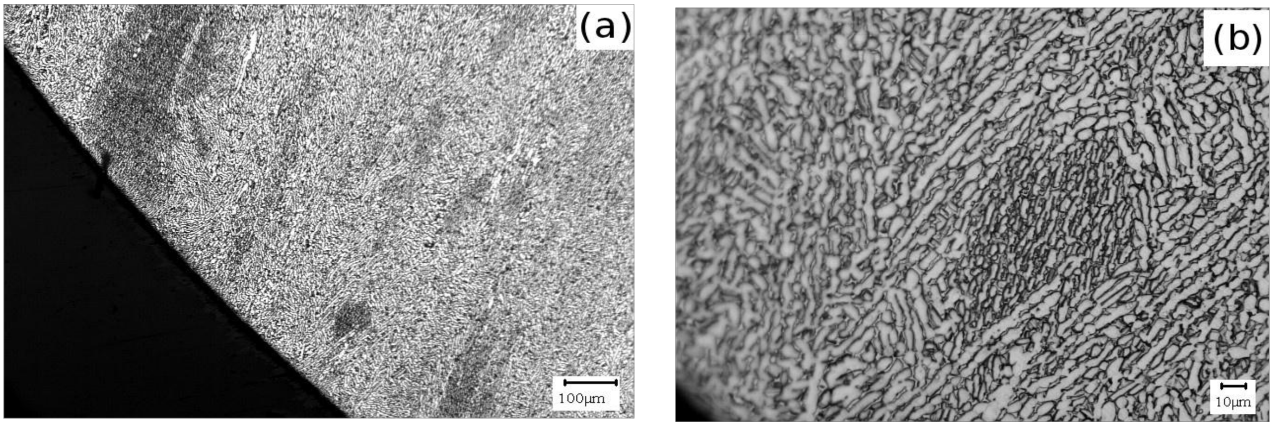


Fig.5. Areas with a fine-grained structure.

As shown on Fig.5. the fine-grained area could be as localized in small region with linear size around 40-50 μm, as a continuously distributed within a big ~~laminar structure~~lamellar structure. In order to get more informations about the mechanisms of crack initiation, observations of crack origination area were carried out by SEM. Results show several types of crack initiation: cracking from (i) strong irregularities of structure (Fig. 6); (ii) areas with ~~unformed (what do you mean? Unformed?)~~a heterogeneity of the formed micro-structure (Fig. 7a); (iii) 'super-grain' formations (Fig. 7b) and (iv) smooth facets (Fig. 8).

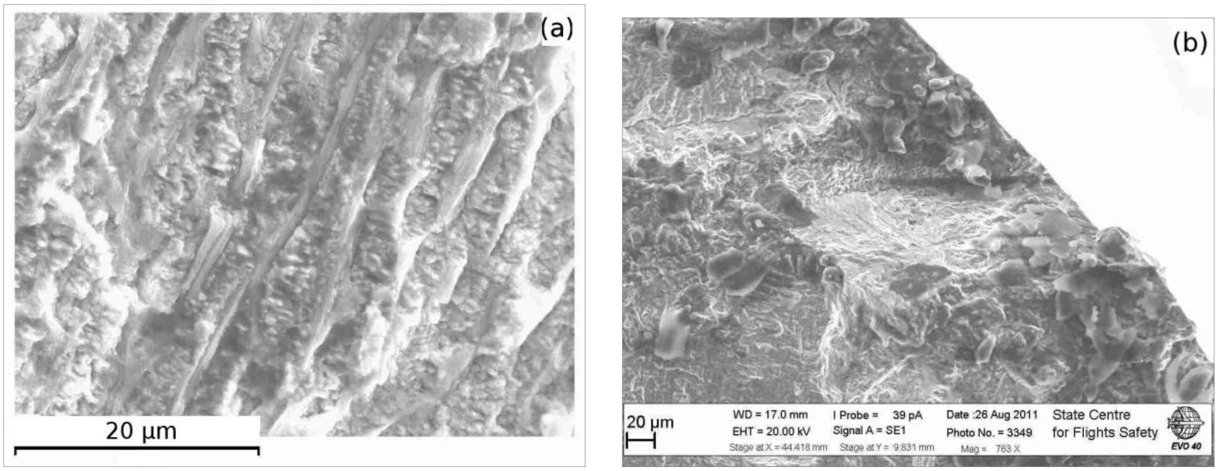


Fig. 6. Two examples (in different specimens) of strong structural irregularities.

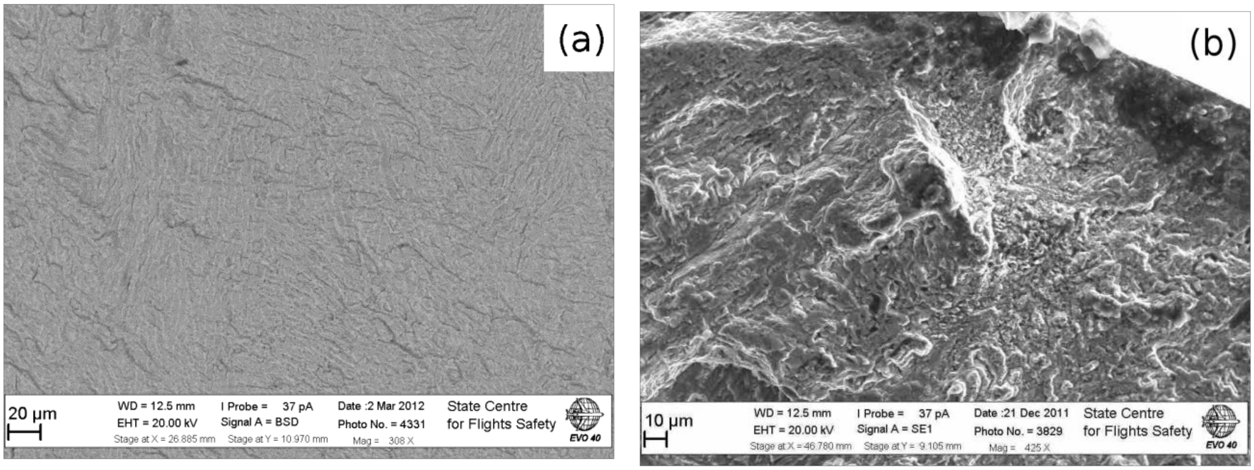


Fig. 7. Examples of (a) ~~unformed (what do you mean? Uniform?)~~heterogeneity of the formed structure; (b) 'super-grain' formation

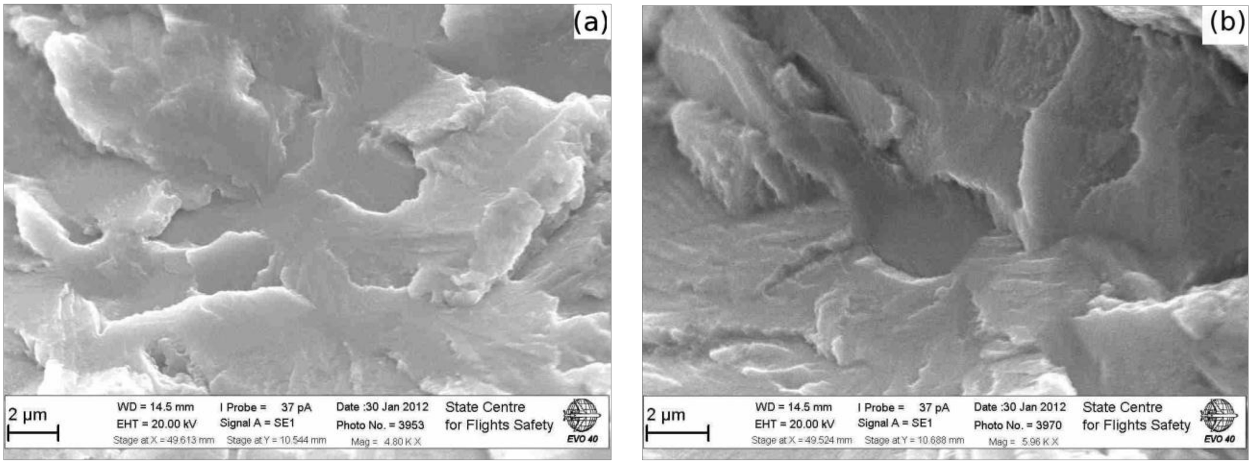
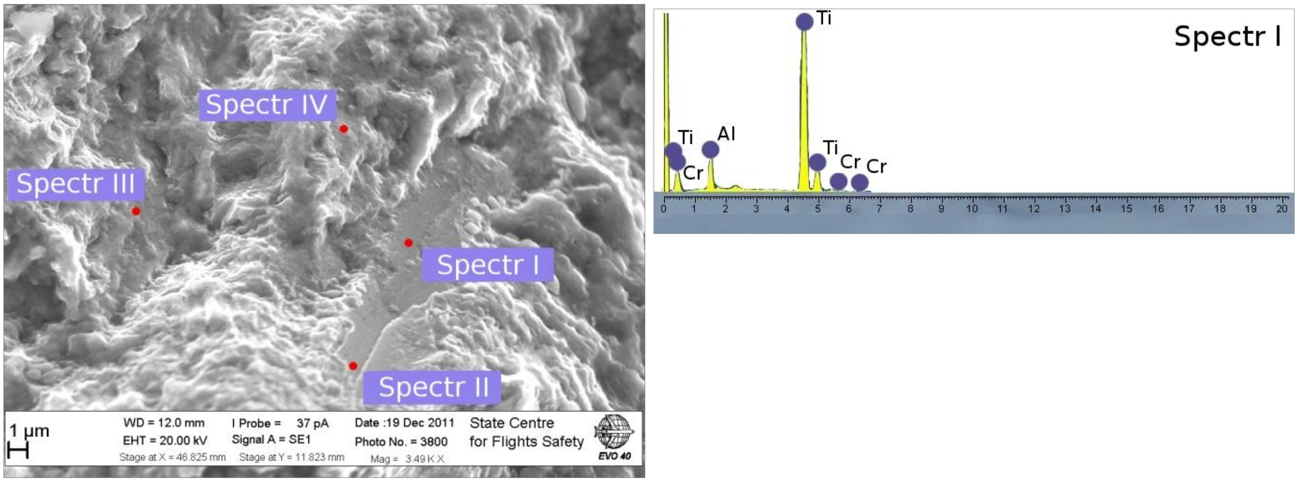


Fig. 8. Crack initiation in two locations from the 'smooth facet'

Greatest scientific interest is the study of the crack initiation from the smooth facet, because this type of crack origination represents a reaction of material without any irregularities of micro-structure on cyclic loading. An additional investigation of crack initiation from the smooth facet was done by using local spectrum analysis, Fig. 9.



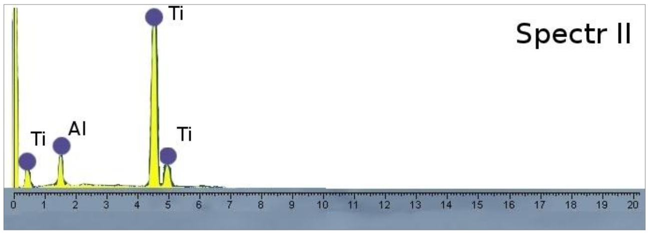
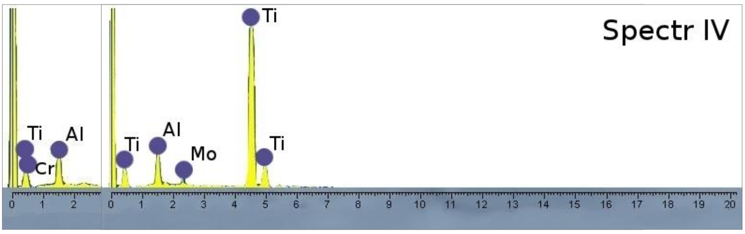


Fig. 9. Spectral analysis of the crack origination area from the smooth facet.

Results of spectral analysis show, that in area of crack origination there is a region with low content of molybdenum. With moving away from the crack initiation area a content of molybdenum is normalized. In order to clarify this experimental result an observation by SEM in regime back scattered electrons was carried out. The result of this investigation is shown on figure 10.



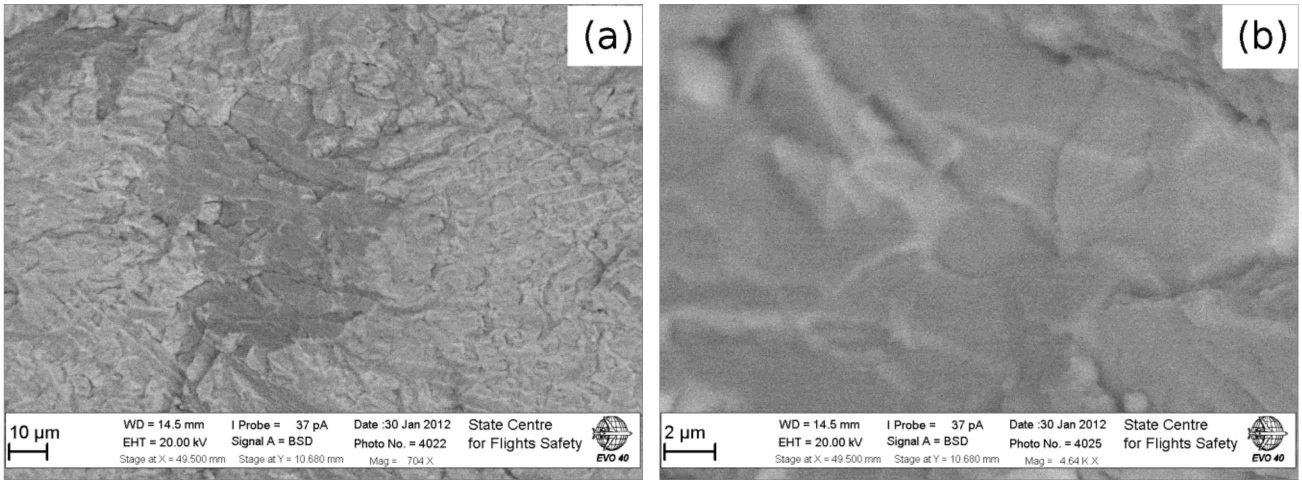


Fig. 10. Observation by SEM of the crack initiation area (from the smooth facet) in regime of back scatter electrons (right picture is a zoom on the center of left picture)

Results and discussions

Observation on the fracture surfaces had revealed two main locations for the crack origination zone. Most of ~~the~~ specimens exhibit an internal position of the crack initiation area, but several specimens have a surface crack origination too. As a rule, surface crack initiation appears under higher stress levels. With decreasing stress amplitude below 400 MPa no surface crack origination was observed. Such distribution of results on the location of crack origination is in good agreement with a bimodal concept of fatigue life [7]. According to this concept, the SN-curve is described by two probabilities of failure. First probability is related to surface cracks and decreases with decreasing the stress level. Second probability is related with subsurface cracks and increases with decreasing of stress level. Bimodal concept does not assume an existence of the fatigue limit (or threshold and infinite fatigue life). SN-curve for titanium alloy Ti-6Al-4Mo also shows permanent decreasing of the fatigue strength with increasing the number of cycles. This result is in good agreement with fatigue data for some types of steels and cast iron [8]. Moreover, experimental results on fatigue life of the titanium alloy Ti-6Al-4Mo (VT3-1) have shown a large scatter of fatigue durability beyond 10^7 cycles. In order to clarify the reason of such fatigue behavior of the material in gigacycle regime an observation of fracture surfaces was done. Results of fractographic analysis shows, that fatigue life of tested specimens strongly depends on features of micro-structure. Identified in the investigation strong defects of micro-structure were more typical for samples with shorter fatigue life. The majority of strong defects are due to some deviation in conditions of production process. Thus, for example, the system of parallel layers shown on Fig. 6a could be a result of accelerated grows of alpha-phase, when beta-stabilizing elements are moved from the zone of alpha-phase formation~~ [9]~~. Even more shorter fatigue life (1.899x10^4 cycles under 385 MPa) has a specimen with a~~n unformed~~ heterogeneity of the formed micro-structure (Fig. 7a). Generally, in the case of a well formed micro-structure and absence of strong defects, the fatigue life is longer and failure determined by cracking from the smooth facets (Fig.8) or special 'super-grain' formations (Fig. 7b). Due to the lack of enough experimental data for cracking from super-grains it is difficult to conclude about the role of such formations on the fatigue life. Theoretically, an influence of super-grains as crack initiation factor should be less compared with strong defects, but stronger compared with a material without any irregularities of structure.

The smooth facet is a fundamental facilities to relax strain energy under a cyclic loading in material with normal structure. Thus, the mechanism of the smooth facet formation and cracking from it, is a key point to understand regularities in the fatigue behavior of titanium alloys. Analysis of smooth facets by SEM at high magnifications leads to the assumption, that such type of fracture surface could be formed just~~ under~~ due to the shear stress under compressing conditions. Figure 8a shows absolute smooth facet surrounded by spiral crack branches. The model of smooth facet formation was proposed by A. Shanyavskiy in 2010 [~~9~~9]. This model assumes the existence in a material of a thin layer of twisted material which kept weakening because of a gradually accumulated damage. In time, the damage can grow to a critical level. Next, a plastic zone begins to rapidly form along the border of the twisted area. Owing such a zone and residual stress brought in with plastic deformation, the material around the weakened area tends to extend and, thereby, makes a smooth facet and opened crack.

Anyway, an area of crack origination has a big scientific interest for studying mechanism of fatigue damage accumulation. In order to get more information about regularities of such areas an additional investigation by spectral analysis on the crack initiations zone for different specimens had shown a deviation of chemical composition in area of crack occurring. As a rule, a region of crack initiation has very low content of molybdenum, so low, that device for spectral analysis does not determine it as a element of chemical composition. Up to now the nature of this phenomena is not clear. Is there formation of zone without molybdenum due to the fatigue test or is it in the material before the test procedure? This question is open. Spectral analysis gives some information, which could be a base for an assumption: this zone may be formed due to fatigue test. Point is that, if we do spectral analysis for areas, surrounding a zone of the crack origination, we will find a permanent increasing of molybdenum content with moving away from the initiation point. Of course it does not clearly proved the hypothesis, that before fatigue tests such zone does not exist. But an opposite hypothesis about an area with gradient of molybdenum's concentration looks more weak.

In order to determine borders of the area with lower content of molybdenum an observation by SEM in regime of backscattered electrons (BSE) were done. The picture in this regime gives information about chemical composition of the investigated object. The areas with bright light correspond to elements with bigger atomic number (a.m.) ~~(~~or higher concentration of electrons~~)~~, dark light correspond to lower concentration of electrons. ~~Based on r~~Results of spectral analysis and observation in regime of BSE leads to the following assumption: in the crack initiation area, the chemical composition has a deviation from the normal composition for titanium alloy. The molybdenum is replaced by aluminum in the zone of the crack origination. The dark color of the image from BSE analysis means that concentration of electrons is lower here, compared with a normal chemical composition. Therefore, the place of molybdenum (element with atomic number 42) is replaced by elements with lower atomic number~~ (not titanium).~~.

Conclusion

Fatigue tests and analysis of fracture surface have shown a a permanent decrease of the SN-curve for titanium alloy Ti-6Al-4Mo (VT3-1) with increasing the loading cycles. The difference in fatigue strength at 10^6 and 10^9 cycles reaches 60 MPa. Beyond 10^7 cycles experimental data on fatigue life have a scatter in 3 orders of magnitude. The nature of so large scatter is in the microstrucrure of the material. Three types of crack initiation from microstructure irregularities were founded: ~~non formed~~heterogeneity of the formed structure, strong defects due to production process, super-grain formation. Moreover, crack origination from a smooth facet was discovered like a general mechanism of crack initiation in titanium alloy. Difference in fatigue life under one stress level is related with the crack initiation factor. Shorter lives correspond to initiation from the ~~non formed~~heterogeneity of the formed structure and longer-one related with the smooth facet formations. For the first time, the phenomena of variation in chemical composition in area of crack origination was observered.

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