FATIGUE BEHAVIOR OF TWO-PHASE TITANIUM ALLOY IN VHCF REGIME

A. Nikitin [1,2], A. Shanyavskiy [3], T. Palin-Luc [4]
[1] MAI – National Research University, Volokolamskoe, 4, Moscow, Russia
[2] ICAD, 2nd Brestskaya, 18/19, Moscow, Russia
[3] Aviation Register, Sheremetievo-1, PO Box 54, Chimlovskiy state, Russia
[4] Arts et Metiers ParisTech, I2M, CNRS, Esplanade des Arts et Metiers, Talence, France

ABSTRACT

This paper is focused on fatigue crack initiation and early growth in two-phase titanium alloy VT3-1 (similar to Ti-6Al-4V) under VHCF loads. The material was produced by two different processes: forging and extrusion. Each kind of material was investigated under three different loading types (push-pull, pull-pull and fully reversed torsion). Fracture surfaces of the tested specimens were analyzed by scanning electron microscopy (SEM) for getting information on crack initiation sites and surrounded fracture surface zones. The results of such analysis were compared with microstructure of the titanium alloy for establishing a crack initiation and early crack growth mechanisms. It was found that crack initiation in this alloy is caused by single or an agglomeration (“cluster”) of alpha-platelets. Under fully reversed tension the fatigue life seems to depend on the geometry of alpha-platelets clusters whereas under tension tension loading such dependence was not observed. However, materials with larger alpha-platelets clusters (macro-zones) have a lower VHCF resistance. The comparison of tension and torsion VHCF test results show a higher slop of the S-N curve under torsion than under tension for both forged and extruded titanium alloys. Nonetheless, some similarities in crack initiation and propagation scenarios were outlined between tension and torsion loadings.

KEYWORDS

Crack initiation mechanism, Ultrasonic torsion, Titanium alloy, Microstructure

INTRODUCTION

The problem of fatigue resistance in aeronautic industry is very important [1]. Some elements of turbojet engine can experience many cyclic loads at high frequency (vibrations) [2]. Acting for a long time they could load the material in the gigacycle regime. The problem of VHCF resistance of structural aeronautic materials is not a simple task due to complex interaction between VHCF strength of materials and their microstructure. As it is well known, crack initiation in gigacycle regime is related to the accumulation of micro-plasticity at microstructural defects [3]. The aeronautic titanium alloys are typically assumed as defect free materials. Nonetheless, it was experimentally shown that subsurface crack initiation may occur in such materials after 10^8 cycles or more [4]. The crack initiation in this case is related to microstructural features of the alloy such as individual alpha-platelets or its agglomeration (“clusters”). The analysis of fracture surfaces in titanium alloys has shows that a more common mechanism of subsurface crack initiation is faceted fracture [5]. Regardless that many research groups have observed fractured facets in titanium alloys [5-10] a common explanation for its formation is still under discussion. This is also due to the fact that morphologies of fracture facets are different. Some authors have observed single fractured facet at the crack initiation site [9, 11] while others show multi facets fracture [5]. Sometimes the fractured facet exhibits a perfectly smooth fracture plane while sometimes a kind of relief can be observed on fractured facet surface [5]. These different features of facet morphology lead to different interpretation of crack initiation mechanisms. The flat facet formation is supposed to be due to cleavage or quasi-cleavage fracture of alpha grains that is similar to the mechanism observed in HCF regime [12]. The quasi-cleavage fracture is explaining by high strain incompatibility between phases in two phase titanium alloys. The rough morphology of facets is formed due to cyclic slip activity within alpha grains [11, 12]. It is important to note that there is no information about the material (i.e. the phase) where both smooth and rough facet formations were found. Therefore a technological process could affect dominant crack initiation mechanisms. In order to study a possible effect of production process the material for present tests was obtained by two different procedures: forging and extrusion. Addiction of titanium alloy to fractured surface crack and strain incompatibility could also lead to unusual fatigue behavior under mean stress [12, 13]. In order to study the effect of mean stress in the VHCF regime, some tests on the VT3-1 titanium alloy were performed with two different loading ratios. Moreover, there are just a few results on the same titanium alloy subjected to different loading types. In practice some components of turbojet engine, such as blades, could experience different loadings types and R ratios. For example the blade can be subjected to high frequency vibration superimposed on static centrifuge force leading to positive loading ratio. Another possible loading type is torsion due to non uniform and not stationary distribution of air pressure on the blade. Therefore, the study of loading type and R ratio on fatigue crack initiation and early growth in aeronautic titanium alloy is an important problem. This paper is focused on the investigation of the fatigue strength of a two-phase titanium alloy in VHCF regime under different loading types and R ratios.

MATERIAL, EXPERIMENTAL PROCEDURE AND RESULTS

Material

The investigated material is the alpha-beta titanium alloy, VT3-1, that is commonly used for aeronautic applications in Russia. Its standard chemical composition is presented in Table 1. The main alloying elements are aluminum, molybdenum and chromium.

Table 1: Chemical composition of VT3-1 titanium alloy (%w)

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

For this study, the VT3-1 titanium alloy was produced by two different technological processes: forging and extrusion. The forged VT3-1 specimens were machined from a real compressor disk of the turbojet engine D30 that is usually installed on Tupolev 154 aircraft. The disk was in service on a Tu-154 aircraft for 6,000 flights before VHCF tests. This period is a regular lifetime for such elements guaranteed by the company. After the in-service the turbine disk was replaced by a new one and subjected to non-destructive analysis for fatigue crack detection. No notable degradation of the material (fatigue cracks, localized plasticity or defectiveness) was detected after these 6,000 flights. The extruded titanium alloy was produced as cylindrical bars with an external diameter of 10 mm. Extruded titanium alloy was treaded for having a needle like microstructure that was similar to the forged VT3-1 alloy. The microstructures of both forged and extruded VT3-1 titanium alloys are illustrated in fig. 1.

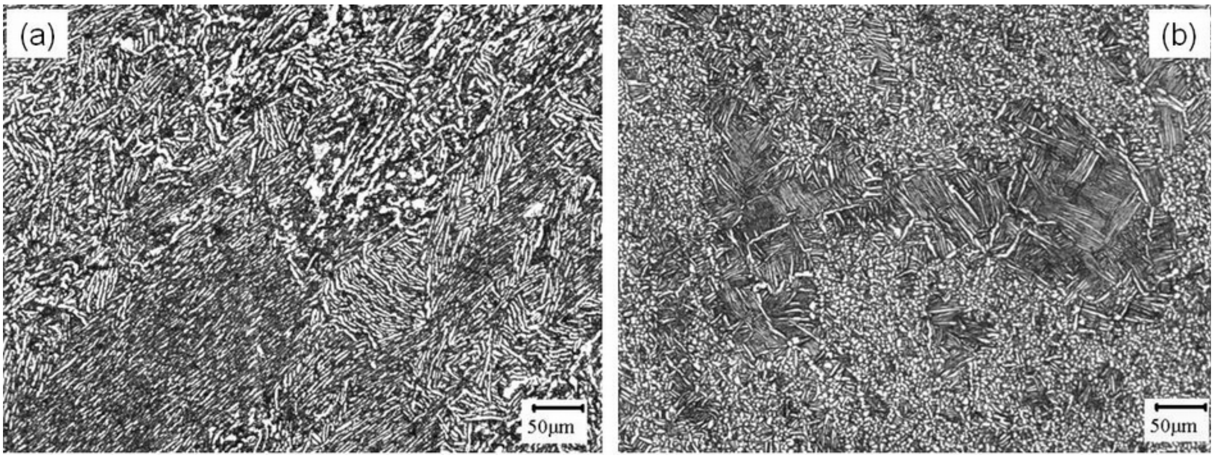

Fig.1: Microstructure of (a) forged and (b) extruded VT3-1 titanium alloys after etching.

The microstructure of these titanium alloys contains elongated alpha-platelets separated by very thin beta phase. These alpha-platelets are bigger in forged titanium alloy than in extruded one. The microhardness of extruded VT3-1 is slightly higher than the microhardness of the forged titanium alloy: 373 HV_{500} and 364 HV_{500} respectively.

Test conditions and results

Fatigue tests were performed with an ultrasonic fatigue testing system at 20 kHz in laboratory air. Hourglass specimens were used for both tensile and torsion tests, details are given in [4, 7]. Fatigue tests were either stopped automatically when the resonance frequency dropped below 19.5 kHz or manually, when the fatigue life becomes greater than 10^9 cycles. The results of the tension fatigue tests under fully revered loading (R=-1) for forged and extruded VT3-1 titanium alloys are shown in figure 2.

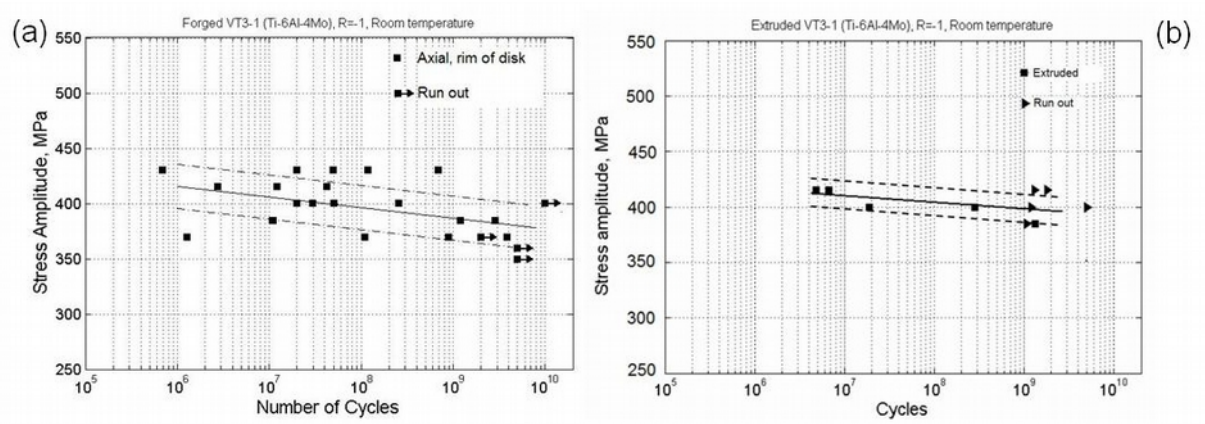

Fig. 2: Results of VHCF tests under tension (R=-1) for (a) forged and (b) extruded VT3-1 titanium alloys.

The S-N curve for the forged VT3-1 is characterized by a large scatter of fatigue life, fig.2a. Such spread of fatigue data is not uncommon for two-phase titanium alloy and was already reported for Ti-6Al-4V alloy [5, 6]. The fatigue strength of the extruded titanium alloy is slightly higher than for the forged VT3-1. However when considering the scatter of the fatigue data one can say that under fully reversed tension the fatigue strength is the same. Both S-N curves have a clear decreasing tendency. The scatter of the fatigue life is higher for forged

VT3-1 than for the other alloy. This can achieve three orders of magnitude at certain stress levels. Unlike results of push-pull tests, the results of tension tests with positive mean stress are quite different for forged and extruded titanium alloys, figure 3.

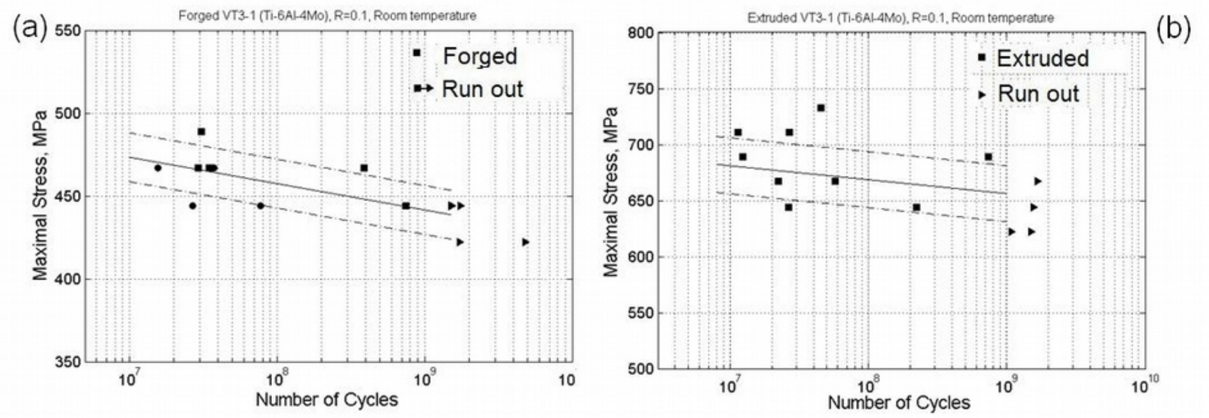

Fig. 3: Results of pull-pull VHCF tests (R=0.1) for (a) forged and (b) extruded VT3-1 titanium alloys.

Under tension (R=0.1), the VHCF strength of the extruded titanium alloy is higher compared to the forged one. The resistance of the forged titanium alloy against VHCF with positive mean stress is very low and cannot be correctly assessed neither by Gerber, nor Goodman models. The slop of the S-N curves is lower under tension with positive mean stress than under fully-reversed tension. However, under torsion this conclusion is not valid. Indeed, the results of torsion tests in VHCF regime, illustrated in figure 4, show the higher slop of the S-N curve between all the obtained results.

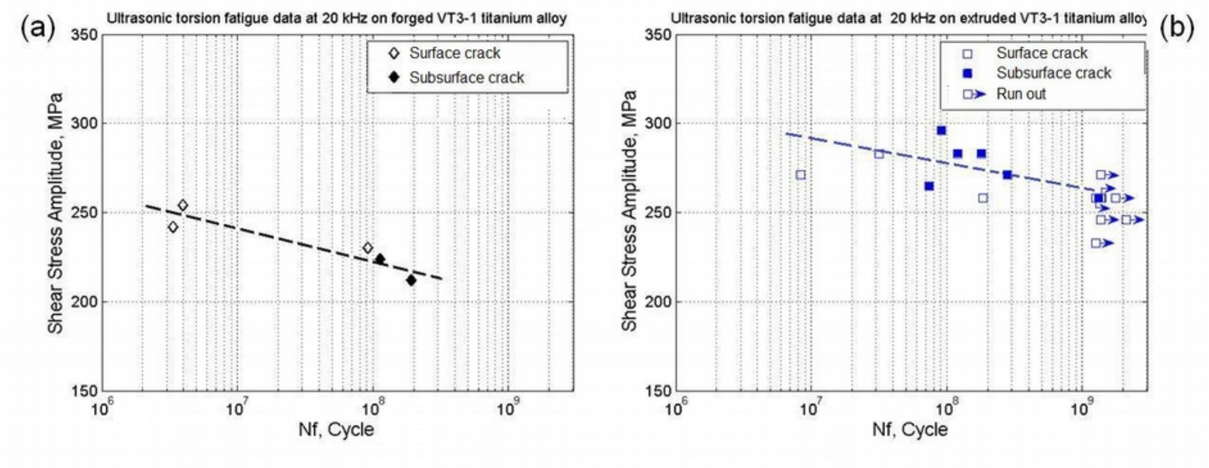

Fig. 4: Results of torsion (R=-1) in VHCF regime for (a) forged and (b) extruded VT3-1 titanium alloys [7].

In order to compare the results of torsion and tension tests the Von-Mises equivalent stress amplitude were calculated. A similar comparison was already donein HCF regime [14]. In the case of HCF result the Von-Mises equivalent stresses gave a good agreement between tension and torsion fatigue results. In the case of VHCF these calculations gives a good agreement between tension and torsion data for the forged VT3-1. But for the extruded one the Von-Mises equivalent stress amplitudes in torsion are always higher than that under tension.

Fracture surfaces

SEM analysis of the fracture surfaces on forged and extruded VT3-1 titanium alloy has shown subsurface crack initiation for both kinds of Ti-alloys. Moreover, subsurface crack initiation was observed for all the studied loading types including torsion. Examples of subsurface crack initiations under tension and torsion loadings are shown in figure 5.

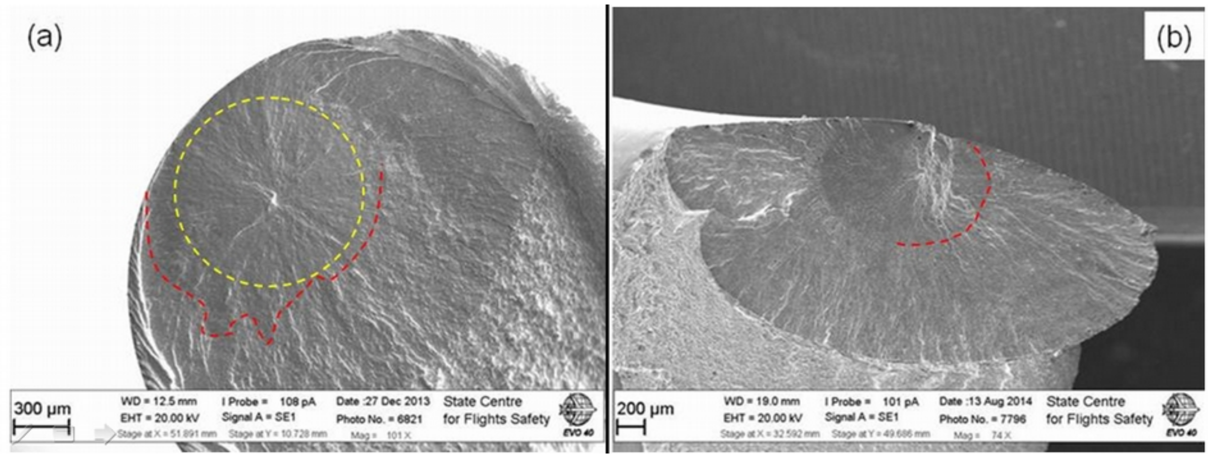

Fig 5: Subsurface crack initiations under (a) tension (R=-1) and (b) torsion (R=-1) loadings in VHCF regime.

Detailed analysis on crack initiation site has shown different types of subsurface crack initiation. In the case of forged titanium alloy both flat and rough fractured facets were found under tension loads. In the case of extruded VT3-1 the crack initiation is related to the fracture of alpha-phase platelets agglomeration. Therefore there is no evidence of flat facet fractures. Similar crack initiation from agglomerations of alpha-grains was observed in forged titanium alloy. However the typical size of alpha-grains within these agglomerations is different for forged and extruded alloys. In the case of extruded VT3-1 the alpha-platelets are extremely thin (less than 1 micrometer in width) while in the case of forged alloy the alpha-grains within agglomeration are large. Thin alpha-platelets are also observed in forged titanium alloy, but they mainly forms large zones (up to 1 millimeter) that are known in literature as 'macro-zones' [15]. In both cases the crack initiation site is located in the bulk of the material. At the center of the fatigue crack no inclusion was observed, but a broken microstructural element can be seen. In the case of torsion load such microstructural element is less recognizable because of fracture surface destruction due to crack lips friction (wear). The crack initiation site is surrounded by a zone that is optically darker (red dashed line on Fig.5). This zone limits a subsurface stage of fatigue crack propagation. The morphology of this zone is smoother than the relief of the next bright zone.

DISCUSSION

The analysis of the S-N curves for the two Ti-alloys under the different loadings has shown a permanent decrease of the VHCF strength versus the number of cycles, Fig. 2 – Fig. 4. But these slopes are not the same for the different loading types. The higher slopes is under torsion. S-N curves slopes for the extruded VT3-1 are slightly lower than for the forged titanium alloy. The VHCF strength of the extruded alloy is higher than that of the forged one. This can be explained by its higher mechanical resistance under monotonic quasi-static loading: the ultimate tensile strength (UTS) of the extruded VT3-1 is 1100 MPa against 980 MPa for the forged one. Forged titanium alloy has a large scatter of fatigue life According to [8] the large scatter of fatigue life is usually observed in Ti-alloys under stress levels corresponding to the transition in crack initiation mechanisms from surface to subsurface. In the case of VT3-1 titanium alloy the large scatter is observed for subsurface crack initiation only. All the fatigue data beyond 10^7 cycles, fig.2a, show subsurface crack initiations. The analysis of the fracture surfaces has shown that the morphology of subsurface crack initiation sites is quite varying. Behind fractured facets the crack initiation from alpha-grain agglomerations, 'macro-zone' borders and primary beta-phase grains were found. The crack initiation is located at different distances from the specimen surface but there is no correlation between internal location and fatigue life. Similar result was already reported for titanium alloys [9]. However, a correlation between fatigue life and crack initiation mechanism in forged VT3-1 can be outlined. It was found that internal crack initiation is caused by different features of microstructure such as agglomerations of coarse alpha-platelets, large macro-zones and single facets. The crack initiation from macro-zones borders and agglomerations lead to shorter fatigue life compared to the crack initiation from single facets. This result is well correlated with results of [10] where these authors state the fatigue life dependence from alpha-grain size. They observed that larger alpha-grain size of titanium alloy lead to shorter fatigue life. The size of agglomerations and macro-zones in forged VT3-1 is larger than single facet.

Regarding the difference of UTS it seems surprising that approximatively the same VHCF strength is observed under fully-reversed tension. However, the analysis of the fracture surfaces of extruded VT3-1 has shown strong heterogeneities of microstructure (figure 6) that were always observed at the crack initiation site. These heterogeneities are agglomerations of ultra thin alpha-platelets that were formed within primary beta phase grains. The presence of such features in the microstructure of the extruded VT3-1 significantly decreases the VHCF resistance of this alloy. The microstructure of forged VT3-1 is represented by different types of alpha-platelets agglomerations from rough alpha-platelets grouped in areas about 20 – 50 micrometers to thin alpha-platelets grouped in macro-zones of several hundreds of micrometers. The high variability of agglomeration sizes and typology lead to large scatter of experimental VHCF results. In the two cases the key parameter is the type of alpha-platelets agglomeration.

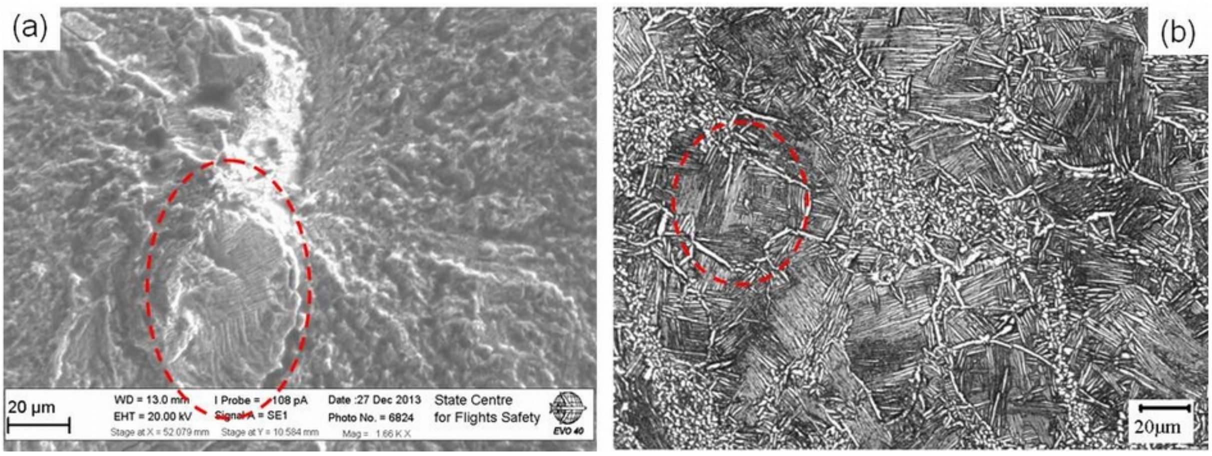

Fig. 6: Heterogeneity of microstructure in extruded VT3-1 titanium alloy: (a) on fracture surface after tension fatigue test in VHCF regime, (b) on micro section after polishing and etching.

Under positive mean tensile stress, the fatigue resistance of the forged titanium alloy in VHCF regime has an important drop. Similar result of stress ratio effect was also reported for forged titanium alloy Ti-6Al-4V under high cycle fatigue (HCF) loading [11]. According to [11] the experimental data for forged material were found below the Goodman line for loading ratios from R=0.05 to R=0.7. The study of the fracture surfaces has shown an important role of material texture in crack initiation. The drop of fatigue resistance under positive loading ratios is explained by cleavage of T-textured alpha grains. The experimental data for VT3-1 titanium alloy under VHCF loading were also found significantly below the Goodman line for R=0.1 while the fatigue results for extruded VT3-1 alloy were found between the Gerber and Goodman lines. An important decrease of the VHCF resistance under positive static tensile force can be explained by large macro-zones that are typical for forged titanium alloy. The fatigue crack initiation sites in this case were found at the macro-zones borders. These borders are barriers for dislocation movement that lead to dislocation accumulation and consequently play the role of fatigue crack initiation trigger.

The analysis of torsion crack fracture surface has shown a significant destruction of the pattern due to crack lips wearing. This does not allow us to investigate in details the crack initiation site. Therefore it is impossible to detect fractured facets under VHCF torsion. Comparison of fracture surfaces obtained under tensile and torsion VHCF loadings has shown some similarities in patterns morphology. In both cases the fatigue crack can nucleate at the specimen surface, as well as in the bulk of the material. In the case of subsurface crack initiation several fatigue crack propagation zones can be clearly outlined. The crack initiation site is surrounded by optically darker area, Fig. 5, that has a very clear border. The darker color can be explained by smoother fracture surface morphology. The drastically change of color is observed where / when fatigue crack turns from subsurface to surface propagation, that is when the environment start to play a role in the crack growth. Typically, the developed surface crack should have a higher stress intensity factor (SIF) range. Therefore, the fracture surface morphology change is related to change in SIF range, and, consequently, in crack growth rate. The same color change was observed for crack under tension and torsion. SIF calculation at the transition line (dashed red line in Fig. 5) gives more or less the same result for both tensile and torsion fatigue cracks. Thus, based on the analysis of tension and torsion fracture surface and SIF calculations at the border transition it can be outlined some similarities in crack initiation and propagation scenarios for tension and torsion loadings in VHCF regime.

CONCLUSION AND PROSPECTS

The results of VHCF tests on forged and extruded VT3-1 titanium alloy has shown that both surface and subsurface crack initiation can be observed in this alloy whatever the technological process and loading type (tension or torsion). The subsurface crack initiation in this alpha-beta titanium alloy is related to the agglomeration of alpha-platelets. The key parameters in this case are the size and typology of these agglomerations. It has been shown that the agglomeration of ultra thin alpha-platelets in extruded titanium alloy can lead to significant decrease of the VHCF resistance under fully-reversed tension. In the case of tests with positive tensile mean stress a critical parameter of the microstructure is macro-zone. The fatigue strength of forged VT3-1 titanium alloy under tension R=0.1 has a significant drop (compared to the extruded one). The fatigue crack initiates at the macro-zone borders in such case. The analysis of the fracture surfaces obtained under tension and torsion VHCF loadings has shown similarities in their fracture pattern morphology with a clear transition from subsurface to surface crack propagation stages. The calculation of the SIF range at the transition crack front gives close results. These results show a similarity in crack evolution scenarios under tension and torsion loadings in VHCF regime. Other investigations should be done under higher R ratio to confirm this conclusion.

ACKNOWLEDGEMENT

A part of this work was realized with the support of the Russian Scientific Foundation, project No. 16-19-10376.

REFERENCES

[1] M.R. Bache, A review of dwell sensitivity fatigue in titanium alloy: the role of microstructure, texture and operating conditions, 2003, Int. J. Fatigue, 25, pp. 1079 - 1087 .
[2] A. Shanyavskiy, Very-high cycle fatigue of in-service air engine blades, compressor and turbine, Science China, 2014, vol. 57, issue 1, pp. 19 – 29.
[3] C. Bathias, P.C. Paris, Gigacycle fatigue in mechanical practice, 2004, Dekker, New-York, 328 p.
[4] A. Nikitin, T. Palin-Luc, A. Shanyavskiy, Crack initiation in VHCF regime on forged t itanium alloy under tensile and torsion loading modes, 2016, International Journal of Fatigue, Vol.93, Part 2, pp. 318 – 325.
[5] J. Everaerts, B. Verlinden, M. Wevers, Internal crack initiation in drawn Ti-6Al-4V wires, Material science and technology, 2016, Vol. 32, Issue 16, pp. 1639 – 1645.
[6] Y. Furuya and E. Takeuchi, Gigacycle fatigue properties of Ti-6Al-4V alloy under tensile mean stress, 2014, Mater. Sci. Eng. A-Struct. Mater. Prop. Microstruct. Process pp. 598, 135-140.
[7] A. Nikitin, T. Palin-Luc, A. Shanyavskiy, C. Bathias, Comparison of crack path in a forged and extruded aeronautical titanium alloy loaded in torsion in the gigacycle fatigue regime, 2016, Engineering Fracture Mechanics, Vol. 167, pp. 259 – 272.
[8] H. Yokoyama, O. Umezawa, K. Nagai and T. Suzuki, Distribution of internal crack initiation sites in high cycle fatigue for titanium alloy, 1997, ISIS Int., 37 (12), 1237 – 1244.
[9] S.K. Jha, C.J. Szczepanski, P.J. Golden, W.J. Porter and R. John, Characterization of fatigue crack initiation facets in relation to lifetime variability in Ti-6Al-4V, Int. J. Fatigue, 2012, 48, pp. 248 – 257.
[10] J. Everaerts, B. Verlinden, M. Wevers, The influence of alpha grain size on internal fatigue crack initiation in drawn Ti-6Al-4V wires, 2016, Procedia Structural Integrity, Vol.2, pp.1055 – 1062.
[11] S.G. Ivanova, R.R. Biederman, R.D. Sisson, Investigation of fatigue crack initiation in Ti-6Al-4V during tensile-tensile fatigue, 2002, Journal of Materials Engineering and Performance 11(2) pp. 226-231.
[12] D.F. Nael, P.A. Blenkinsop, Internal crack origin in alpha-beta titanium alloy, 1976, Acta Metal, 24, pp 59 – 63.
[13] A.M. Freudenthal, New aspects of fatigue and fracture mechanics, Engineering Fracture Mechanics, 1974, 8 (6), pp. 775 – 93.
[14] C. M. Sonsino, H. Kaufmann, V. Grubisic, Transferability of material data for the example of a randomly loaded truck stub axle, SAE Tech. paper series, 970708, (1997), pp. 1-22.
[15] K. LeBiavant, S. Pommier and C. Prioul (2003) Local texture and fatigue crack initiation in Ti-6Al-4V titanium alloy, Fatigue Fract. Engng Mater Struct. vol.25, pp. 527-545

Corresponding authors: nikitin_alex@bk.ru and thierry.palin-luc@ensam