SUBSURFACE SHORT CRACKS PATH IN TI-6AL-3MO-0.4SI TI-ALLOY

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ABSTRACT. *The phenomena of fatigue crack origination subsurface in slightly surfacesly-hardened specimens of titanium alloy VT3-1 (Ti-6Al-2Sn-4Zr-2Mo-0.1Si) has considered based on Acoustic Emission monitoring during specimen tests. It has shown that area of origin creation and short crack growth take place subsurface during unloading portion of cyclic loads. Crack path analysis based on fractograpnic consideration of several areas of origins has revealed that the twisting (or mode III crack opening) mechanism is dominant manner of material damage accumulation to create first facet of the origin area. Then, there is the short crack propagation around the first facet under combination of modes III and I crack opening to create fracture area. The introduced model of the subsurface material cracking because of twisting mechanism has discussed based on well-known results of numerical estimations of subsurface metals stress-state evolution during its plastic deformation on the meso-scale-level.*

INTRODUCTION

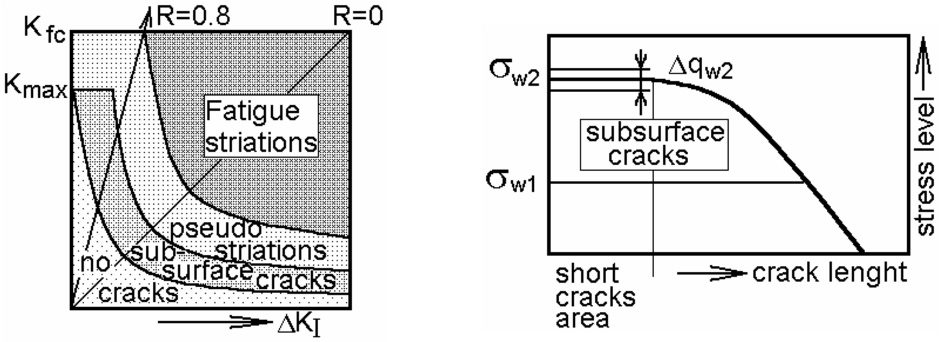
The phenomena of fatigue crack origination subsurface related to the metals behavior in Ultra - or Very -High-Cycle-Fatigue (VHCF) regime [1]. The main idea introduced to explain the metals possibility to originate the subsurface fatigue crack based on the influence of inclusions stress-state (constrain) because cracks origination take place from inclusions.

For Ti-based alloys, crack origination subsurface can be without influence of inclusions [2]. The discussed situation takes place for two-phase ($\alpha + \beta$) Ti-based alloys with lamellar or globular microstructures. Two situations of metals cracking were discovered in area of subsurface crack origination: (1) the point of origin places at the boundary of two grains or plates; (2) the origin area creates because of quasi-cleavage one grain or one plate.

It is well known Kitagawa-Takahachi diagram [3] that divided areas of not fatigued and fatigued metals with different size of cracks. In fact, that in the stress range of stresses Δq_{w2} [4] near the “fatigue limit” can bee seen [5] surfacesly short fatigue cracks growth that have not transition to the long cracks. Applicably to Ti-based alloys, R-ratio has such influence on the ratio between stress intensity factor range and its maximum value $\Delta K/K_{max}$ when cracks have initiation at the metal surface, that shown in Fig.1.

Now evidently [4], that all surfacesly short cracks took place in bifurcation area Δq_{w2} that is the transition area from HCF to VHCF regime (see Fig.1b).

The first stage of subsurface crack propagation has discussed as the short crack propagation. Nevertheless, it is not the same situation for cracks development at- and subsurface. The principal difference in these two situations for crack propagation takes place because of (1) environment effect, and (2) stress-state (constrain factor).



a) b)

Figure 1. Reorganized diagram (a) to describe R-ratio influence on the fatigue cracking of different types of Ti-based alloys and reorganized Kitagawa-Takahashi diagram (b) with stress levels σ_{w2} of „fatigue limit" and σ_{w1} ranged area for subsurface cracks and the bifurcation area Δq_{w2} [4] where can be seen non-propagated surfacesly short cracks.

Short cracks propagation before are stoped take place at the surface under the biaxial stress-state. These short cracks can propagate under well-known effect of sliding [4] with environment influence. In fact, the stress-state for subsurface developed cracks is three-axial, and crack origination takes place without environment influence. In this case, the sliding process in material volume cannot be done in the same manner as for the surfacely cracks because there material has not free area for increment of material cracking under the sliding because of in- or extrusions around first facet of the originated crack. Neveretheless, the crack increment for surfacesly crack is realized during unloading portion of cyclic loads during fatigue striations formation [5].

Below subsurface crack path of titanium alloy VT3-1 is considered, and crack propagation during unloading portion of cyclic loads has discussed.

MATERIAL AND EXPERIMENTAL PROCEDURES

Material and specimens

The titanium alloy VT3-1 (Ti-6Al-2Sn-4Zr-2Mo-0.1Si) has used in fatigue tests. This type of material had after manufacturing procedure for compressors disks of aircraft engines Ultimate tensile strength in the range of 1040-1100 MPa with elongation and section area reduction respectively (10.8-16) % and (3.1-4.7) %.

Specimens for tests have cut out from the disks of the second stage one of the engine compressor. Finally manufactured specimens has been subjected to heat treatment (HT) with tempering at T = 530°C within 6 hours, and then cooling on air [6].

Round bar specimens of 8mm in diameter with circular notch of 2 mm in depth with stress raiser with concentration factor near to 1.46 have used in these experiments.

Specimens were then subjected to surface-hardening treatment with either hydraulic shot-peening (SP) by microballs with diameters in the range of (0.05-0.3 mm). The hardening degree was in the range of 1.1-1.27. The residual stresses were introduced in the depth direction not more that 0.2 mm.

Tests and investigation procedures

The analysis of structure of titanium alloy VT3-1 on several specimens has been executed in the regime of backscatter electrons in the scanning electron microscope of the "Karl Zeiss" instruments. With this purpose have been prepared slices from specimens in a plane, it is perpendicular their axes. The mixed globular and lamellar ($\alpha+\beta$) two-phase microstructure being typical for disks material has demonstrated.

Primary, specimens were subjected to symmetric and asymmetric tension-compression on the hydraulic test machine with frequency of 35 Hz at environment temperature 20°C. The maximum stress level was in the range of (140-920) MPa with stress R-ratio in the range of (0.3-0.67) for tension and at R=-1.0 for tension-compression [6].

Second, the fatigued specimens were investigated in the scanning electron microscope to establish the fatigue crack origination area and to choose the cyclic loads range which can be used for investigation nature of the fatigue crack origination and short crack propagation subsurface. Then three specimens were tested under tension at the maximum stress level 820 MPa and stress ratio 0.48 with frequency 35 Hz.

During tests, there were performed Acoustic Emission (AE) monitoring for the registration of the moment of the fatigue crack origination. The main idea of the crack detection in fatigue tests is based on the introduced earlier "α-criterion" [7, 8]. The summarized AE-signals in versus number of cycles have drastically transition to acceleration at the crack initiation at the surface. If registered, the test continued during several hundred cycles for clear evidence of the "α-criterion" - it is increased angle of the discussed dependence. Then the test stopped if the crack origination area has to be analyzed without interest to the stage of the crack propagation. More ditaled information about AE-method can be taken elsewere [7].

In the discussed case for the subsurface crack path, only one specimen considered below because of several cracks had subsurface origination before tests had stopped. Situation with the single subsurface crack origination has discussed earlier [8].

After the fatigue test of specimen up to 415,104 cycles, it was subjected to monotonic tension with speed of deformation 0.01mm/min up to the fast fracture.

The opened fracture area has cut from the specimen and investigated in scanning electron microscope.

INVESTIGATION RESULTS

AE signals path

Revealed AE signals versus number of cycles in tests for the investigated specimen shown in Fig.2.

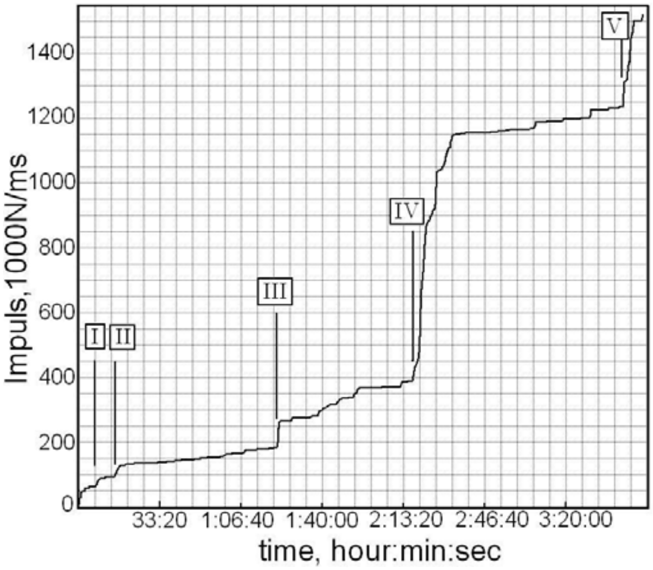


Figure 2. Number of AE-impulses in versus time of cyclic loading for specimens of Ti-based Alloy with indication "I-V" drastically changes in speed of AE-impulses

Primary, it very clear seen that the discussed AE-signals sequence in time has several evidently drastically increases that indicated by numbers from «I» till «V». The test has stopped immediately after the fifth drastically change of AE-signals. More clear changes in AE-signals in time seen in the range of points "III-V".

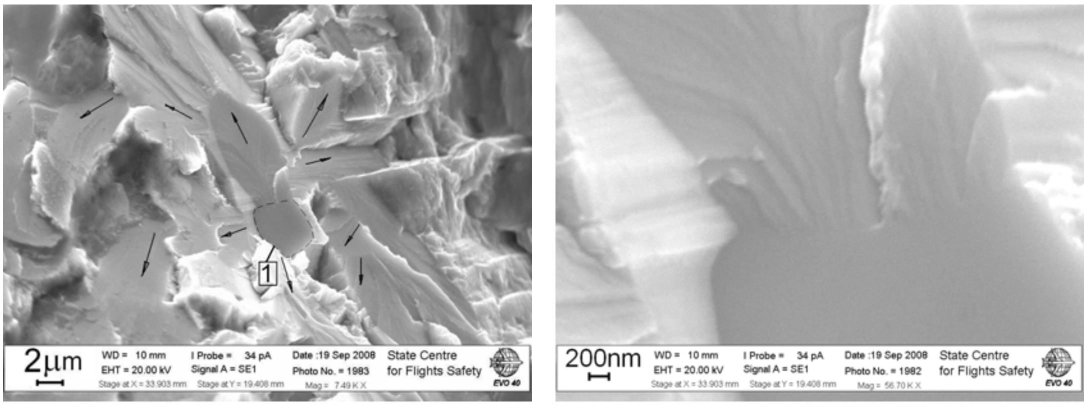
Second, the sequence of the AE-signals has analyzed in versus uploading and unloading portion of cyclic loads. It was established that in area of draslically change of AE-signals intensive their appearance took place in unloading portions of cyclic loads. From the revealed results follow that damages accumulation in the material or free fracture surface formation takes place in unloading portion of cyclic loads when subsurface crack origination and first stape of its propagation occure.

Results of fractographic analyses

The tensed specimen, after the fatigue test, had the shear lips by the circle of its shape. That is why it was not clear where could be placed zone with fatigue fracture patterns.

The performed analysis has shown that there are three areas within the shear lip with fracture patterns of the material quasi-cleavage whith subsurface oriigins, Fig.3.

One of them, numbered "1", had clear registered origin as a smooth facet without steps, lines or "rivers" those occured around the facet, Fig.3b. Cascade of facets with well-known patters such as "rivers" for material quasi-cleavage surrounded this smooth facet. The performed fatigue area from the "1" origin was of the elliptical shape with maximum axes sizes 2a=130 μm, and 2c=260 μm. The minimal distance of the fracture area border was near to 80 μm out of the specimen surface.



a) b)

Figure 3. Overview one of the fatigue fracture areas with subsurface facet of origin, numbered “1”, and (b) the facet border shown under higher magnification. Arrows indicated crack growth direction from the origin.

The next two fracture areas, numbered “2” and “3”, were performed not far from the area “1” on the distance approximately 1mm. They are situated one after another. The place of origin for these two fracture areas was the same that has discussed below for the origin area number “1”, Fig.4. The material cracking by the quasi-cleavage manner took place with steps, lines, or “river” patterns out of the smooth facets. The maximum size of these two fracture areas, numbered “2” and “3”, was 220μm. The distance from the specimen surface of the fracture area border was near to 150 μm.

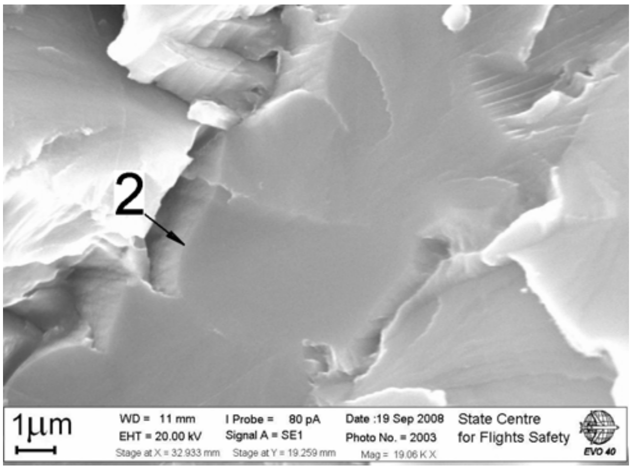


Figure 4. Overview of the fracture area around the facet, numbered by “2”, of subsurface crack origination placed not far from the origin shown in Fig.3.

Therefore, during fatigue tests there were performed several areas of the material fracture within the shear lip placed not far from the specimen surface but crack growth from origins took place subsurface only before test has stopped.

DISCUSSION

Sequence of registered AE-signals versus number of cycles (see Fig.2) was compared with results of fractographic analyses.

It was earlier shown [8], that for the material fatigue cracking at the surface the drastically change of AE-signals sequence versus number of cycles testifies the moment of the crack origination described by the "α-criterion". If registered "α-criterion", the fatigue crack origination at the surface takes place.

Consequently, the discussed cascade of the drastically changes of AE-signals, numbered from "I" till "V" reflects the sequence of the fatigue cracks areas creation. Each discussed point shows the moment of the crack origin formation. The crack propagation after the origination has not the same intensiveness for energy dissipation that accommodates for the first facet of the fracture surface creation.

In fact, the sequence of origins formation cannot be established from the fractographic analysis exactly. However, from this analysis followed several times of AE-signals sequence changes because of several acts of fatigue cracks subsurface originations. The first smooth facet for all origins was the same and it has developed inside of material volume under mode III metal deformation. It is clear because for each origin performed in the manner of the smooth facet there was not evidence of material cracking through one or several crystallographic planes as very clear for other facets surrounded all areas of origins (for example, see Fig.3, 4). However, to explain this possibility for material distress with smooth facet of origin formation, the well-known sliding process cannot be used.

In the case of three-axial stress-state for material volume with two-phase microstructure, there is more effective realizing the twisting deformation by the planes of globules or lamellas. From one to another local place there is not uniformly distributed stress-state under the external tension or compression because globules or lamellas have complicated shapes, various orientations of the crystallographic planes with the same possibility to prevent cracking, and the structure elements interacted under loading with difference intensiveness in various directions by their borders.

The numerical calculations of deformations distribution inside of polycrystalline material were performed [10] based on three-dimensional models for three-axial stress-state. They have shown the next sequence of plastic deformation processes under tension. First, origination and development of plastic deformation occures because of translations take place. Then, there is principally possible of material volumes rotations.

The material plastic deformation analysis on the meso-scale-level shows that borders of grains are volumetric sources of stresses concentration at an elastic stage of loading, and the maximum level of stresses takes place near to threefold joint of grains with the most distinguished elastic properties, Fig.5. The first plastic shears here arise and metals local increments reorientation takes place under monotonous tension in the center of the specimen for thin plate in "t" thickness [10].

In process of loading shears (elastic case of deformations) are distributed from grains boundaries in their volumes (see Fig.5). Thus in an elastic material ahead of front of an elastic wave there is the whirl (under mode III) necessary to accommodate deformation energy of the neighbored areas. Shears deformations and turns (twisting) are distributed on both parties' intergranular borders, penetrating through the whole fragments of a stressed material. The basic accommodation of structure comes to an end formation of a grid of strips of the located deformation providing the further deformation due to shift of formed fragments from each other under torsion.

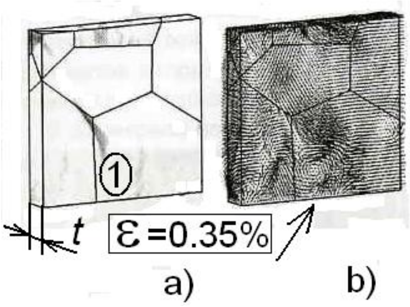


Figure 5. Thin foil (a) of "t"-thickness taken from the specimen center and numerically analyzed this volume deformation (b) with vectors orientation of material displacement in different points under specimen tension at the deformation 0.35% [10]. Number "1" indicated area where takes place rotations shown by arrow.

The most intensive whirl takes place near to threefold joint of grains. In the case when the size of grains (fragments of structure) is in proportion to width of the front of an elastic wave of deformation or exceeds her, there is a turn (twisting) of separate grains from each other. When the grain twisting is not possible under the complicated compression-tension stress-state there performs turns under mode III (twisting in the reversed case) of two grain fragments from each other.

Under unloading portion of cyclic loads, primary, the twisting process of material volumes directed to realize elastic-plastic deformation in a local area without material cracking. There takes place reversible situations of small volume rotations (turns) in one direction during uploading and in another one during unloading portion of cyclic loads.

The reversed elastic-plastic situation for deformed materials can be illustrated based on rotations without volume cracking that take place in the well-known toy named "Cubic of Rubik". There are realized rotations in one and another direction by one or several "planes" without cracking. However, after the critical density of dislocations and/or disclinations exceeded in the discussed titanium alloy by one or several in parallel placed rotated planes, the lamella or globule distress (or ultra-plasticity) takes place under material volume compression and, then, stress concentration around the distressed plane drastically increases that schematically shown in Fig.6. Then the twisting of cracked material around the first created facet has intensification and the short crack propagation from the place of origin performs, around the first facet, by the manner of material cracking under combination of the mode I and III crack opening.

It seems to be the discussed process is dominant for all metals (distress or ultra-plasticity) when subsurface cracking performs in VHCF regime to create fist facet. If inclusions influenced fatigue subsurface cracking, rotations of inclusions and volumes rotations around inclusion directed to realize free of fracture surface with material heating because of high level of plastic deformation that activated diffusion of hydrogen or other gases in the heated volume and covered created free surface by oxides or other compositions during subsurface crack propagation.

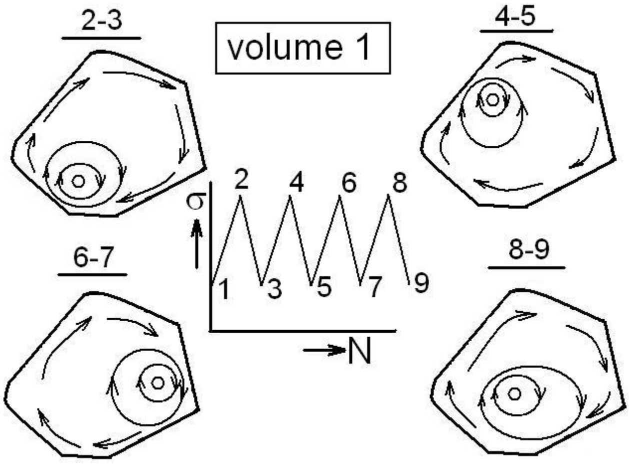


Figure 6. Schema of sequence of events for twisting material volume “1” which occurs in one of the structural element during unloading portion of cyclic loads.

REFERENCES

1. Bathias, C. and Paris, P.C. (2005) *Gigacycle fatigue in mechanical practice*, Marcel Dekker, NY, USA.
2. Shanyavskiy, A.A., Zaharova, T.P., and Potapenko, Yu.A. (2007) In: *Very High Cycle Fatigue (VHCF 4)*, pp. 325-330, Allison, J.E., Jones, J.W., Laresen, J.M., and Ritchie R.O. (Eds), University of Michigan Ann Arbor, Michigan, USA.
3. Takahashi, I., Yoshi, T., Iidaka, H., Fujii, E., and Matsuoka, K. (1993) *Fatigue Engng Mater. Struct.* **16**, 37-51.
4. Shanyavskiy, A.A. (2007) *Modeling of metals fatigue cracking. Synergetics in aviation,* Monograph, Ufa, Russia.
5. Miller, K.J. (1997) *ASTM STP*, ASTM, Philadelphia, **1296**, 267-286.
6. Shanyavskiy, A.A. (2008) In: *LCF 6*, pp. 599-604, Portella, P.D., Beck, T., and Okazaki, M. (Eds), DVM, Berlin, Germany.
7. Shanyavskiy, A.A., Zaharova, T.P., Potapenko, Yu.A. and Artamonov, M.A. (2008) In: *ECF 17*, pp. 321, Pokluda, Lukach (Eds), Brno, Chezh.
8. Shaniavski, A.A., Losev, A.I., and Banov, M.D. (1998) *Fatigue Fract. Engng Mater. Struct.* **18**, 297-313
9. Shanyavskiy A.A., Banov M.D. (2008) In: *Synergetics in nano-technologies application*, pp.350-355, Shanyavskiy, A.A., Ivanova, V.S., Kovalenko, L.V., and Artamonov, M.A. (Eds), Russian State University of Aviation Technology, Moscow, Russia.
10. Romanova V., Balakhonov R., and Makarov P. (2006) *Int. J. Fracture* **139**, 537-544.