Experimental investigation of crack initiation and propagation in high- and gigacycle fatigue in titanium alloys by study of morphology of fracture

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ABSTRACT. Fatigue (high- and gigacycle) crack initiation and its propagation in titanium alloys with coarse and fine grain structure are studied by fractography analysis of fracture surface. Fractured specimens were analyzed by interferometer microscope and electronic microscope to improve methods of monitoring of damage accumulation during fatigue test and verify the models for fatigue crack kinetics. Fatigue strength was estimated for high cycle fatigue (HCF) regime using the Luong method [1] by "in-situ" infrared scanning of the sample surface for the step-wise loading history for different grain size metals. Fine grain alloys demonstrated higher fatigue resistance for both HCF and gigacycle fatigue regimes. Fracture surface analysis for cylindrical samples was carried out using optical and electronic microscopy method. High resolution profilometry (interferometer-profiler New View 5010) data of fracture surface roughness allowed us to estimate scale invariance (the Hurst exponent) and to establish the existence of two characteristic areas of damage localization (different values of the Hurst exponent). Area 1 with diameter ~300 μm has the pronounced roughness and is associated with damage localization hotspot. Area 2 shows less amplitude roughness, occupies the rest fracture surface and considered as the trace of the fatigue crack path corresponding to the Paris kinetics.

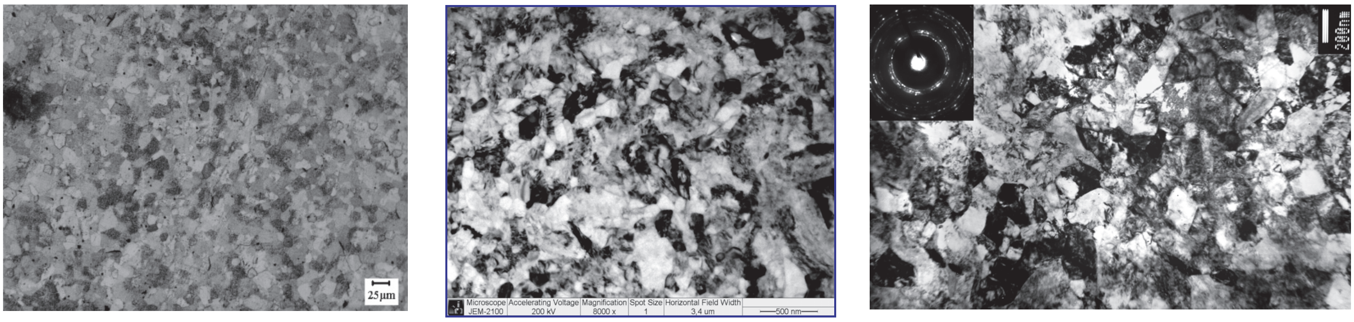
KEYWORDS. Fractography; Gigacycle fatigue; Titanium alloy.

INTRODUCTION

HCF and VHCF are important fundamental and engineering problems for several areas o applications. Catastrophic events caused by failure of gas-turbine motors, high costs of fatigue life-time estimation for constructions and potential cost of development of new constructions initiated perspective conceptions in the area of HCF and VHCF based on the fundamental research in fatigue damage and reliability prediction. The kernel aspects of such programs are development of approaches using the results of fundamental research, modern approaches in the laboratory modeling and structural analysis for the prediction of characteristic stages of fatigue damage and the criticality signs under damage-failure transition. High interest to VHCF is determined during last decade and explaining the opportunity to reach number of cycles 10^8-10^{10} for materials and constructions of gas-turbine motors due to the usage of fine-grain superalloys and advanced technologies providing VHCF limit. Recently, an increase in the strength properties of structural materials has been achieved by the formation of micro-and nano-crystalline structure. However, traditional methods of testing do not provide an estimate of fatigue life in gigacycle loading conditions (10^9 cycles to failure) leading to the emergence of new techniques based on ultrasonic testing machines like [2] and studying the morphology of the fracture surfaces by modern methods of structural analysis. The effect of microstructure in pure titanium including submicrocrystalline (SMC) and Ti6Al4V alloy was studied in gigacycle fatigue regime and qualitative differences in the mechanisms of fatigue crack initiation in high-and gigacycle fatigue conditions established.

EXPERIMENTAL CONDITIONS AND MATERIALS

Specimens of pure titanium with different microstructure from original polycrystalline state with grain size of 25 μm to SMC state obtained through equal channel angular extrusion (ECAE) at different conditions: SMC-1 state (annealing at T = 450 °C, 8 passes of ECAE , drawing from 14 to 9 mm at T = 200 °C, the grain size: 100-150 nm) and SMC-2 state (annealing at T = 450 °C, 4 passes of ECAE, the warm rolling from 12 to 8 mm at T = 350 °C, the grain size of 200 nm) and specimens of titanium alloy Ti6Al4V were investigated in high- and gigacycle fatigue regime using the ultrasonic testing machine. In order to establish the scale invariant parameter [3-5] of crack initiation and growth in high- and gigacycle fatigue fracture surfaces of samples were analyzed.



a) b) c)

Figure 1: Structure of Ti Grade-4: a) optical microscopy image of initial state (grain size ~25 μm); b) TEM-image of SMC-1 state (grain size ~150-200 μm); c) TEM-image of SMC-2 (grain size ~200 μm)

According to transmission electron microscopy the microstructure of SMC-1 material is more homogeneous, grains have equiaxial shape in transverse and longitudinal sections. In the longitudinal section of rod in SMC-2 state we can observe development metallographic structure, which is characterized by elongated grains with dislocation substructure as a result of rolling after ECAE.

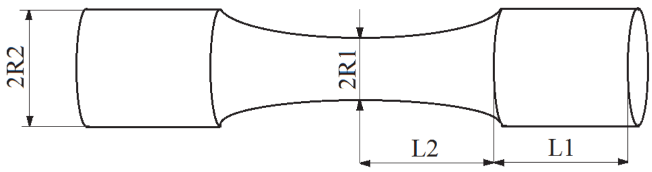


Figure 2: Geometry of specimen. Values of sizes R1, R2, L2, L1 is depends on parameters of material and calculates in formals at [5].

Fatigue tests were carried out on the ultrasonic loading machine Shimadzu USF-2000, which imposes special load conditions due to the geometry of the samples (fig.2). During the experiment, the sample and components of the machine are in resonant oscillations which form a standing wave. In this case peaks of displacement are located on ends of the sample and maximum amplitude of stress is located in the center of sample [5].

RESULTS OF FATIGUE EXPERIMENTS

The result of fatigue tests are shown in the Fig. 3. Fatigue failure of Ti6Al4V after 10^9 cycles occurred at stress amplitude 495 MPa. Failure of samples of pure titanium after 10^9 loading cycles occurred at 275 MPa stress amplitudes for the initial state and 375 MPa and 340 MPa for the states SMC-1 and SMC-2, respectively. Fatigue life of titanium alloy Ti6Al4V in gigacycle regime corresponds to the data of Bathias [5]. The dependence of material microstructure on its fatigue strength during gigacycle fatigue agrees with data observed in [6]. The SMC-1 titanium Ti-Grade 4 with equilibrium grain boundaries exhibits highest fatigue properties compared to the SMC-2 state with non-equilibrium grain boundaries and to the polycrystalline state (grain size of about 25 μm).

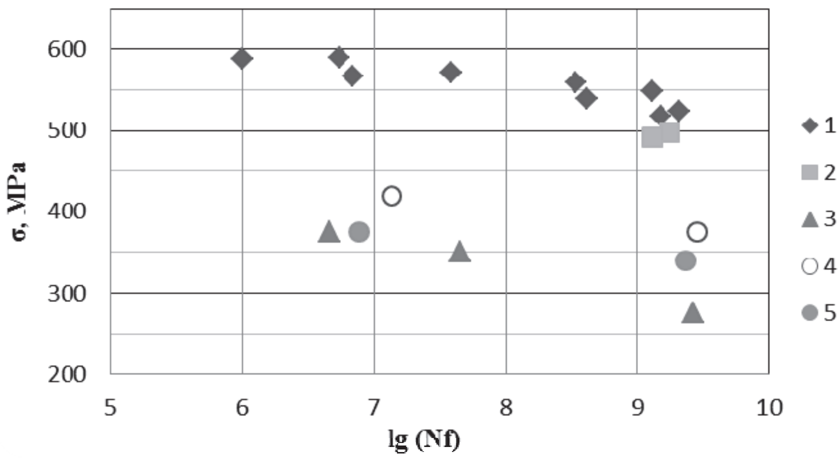


Figure 3: Fatigue curve data for investigated materials: σ – applied mean stress, Nf –number of cycles to failure. 1 – Ti6Al4V Bathias [6]; 2 – Ti6Al4V; 3 – Ti Grade-4 initial state; 4 – Ti Grade-4 SMC-1 state; 5 – Ti Grade-4 SMC-2 state.

Mechanisms of initiation and propagation of fatigue cracks were investigated by means of qualitative and quantitative analysis of the morphology of fracture surfaces. The results of observation reported in [7] show that during stress cycles several fine subgrains having different crystal orientations are formed in a thin layer (thickness is 400 nm) around non-metallic inclusion. The following mechanism of crack initiation under long cyclic loading was proposed: a fine granular layer caused by the intensive polygonization is gradually formed around the interior inclusion. The number of microdamage centers in this layer gradually increases and some of them coalesce. When damage spread over the entire fine granular layer the crack is finally formed around the interior inclusion. After the crack has grown to a critical size, it propagates in accordance with the Paris law kinetics:

$$\frac{da}{dN} = C\left(\Delta K\right)^m, \tag{1}$$

where da/dN is the fatigue crack growth rate, C and m are empiric constants depending on the material, K is the stress intensity factor. Qualitative analysis was carried out by using optical and electron microscopy of the surface morphology.

QUALITY AND QUANTITATIVE ANALYSIS OF FRACTURE SURFACES

Destruction in gigacycle fatigue regime usually forms a characteristic type of fracture surface - "fish-eye"[6-7]. Qualitative analysis by optical microscope allows us to separate zones with different reflectivity. First zone with a radius of 150 μm from the source of crack is very dark, then light and smooth area is followed, which is then replaced by darker area (fig.4). By substituting the radius of the borders in the formula (2) for the stress intensity factor of radial inner cracks

$$K = 2\sigma\sqrt{a/\pi}F[D/(2a)], \tag{2}$$

where F is normalization function [8], D is diameter of the sample, these zones can be associated with the stages of crack nucleation and propagation. Radius a = 150 microns corresponds to the threshold value of the stress intensity factor ΔK_{th} for this material at which the crack begins to grow. In the area between borders of 1 and 2, the crack grows steadily by

Paris law (1). Area between boundaries 2 and 3 corresponds to catastrophically fast growth of crack. The value of K with radius of crack 3 - 1400 μm corresponds to the fracture toughness.

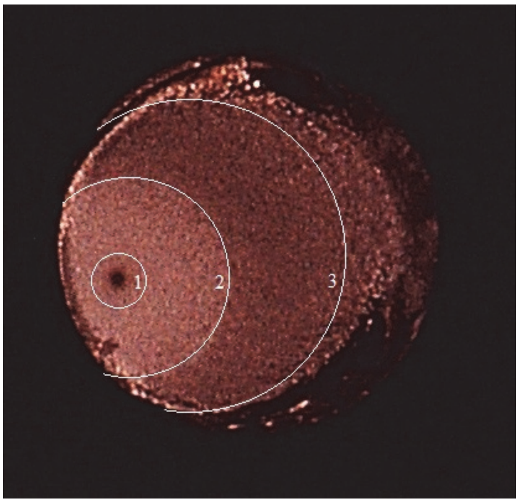


Figure 4: Fracture surface of Ti6Al4V in gigacycle fatigue regime. 1) a= 150 μm, $\Delta K = 6.88$ MPa√m $\approx \Delta K_{th}$; 2) a= 750 μm, $\Delta K = 21.3$ MPa√m; 3) a= 1400 μm, $\Delta K = 54.1$ MPa√m $\approx \Delta K_{1c}$.

The surface roughness was analysed by interferometer-profiler New View 5010 to establish quantitative characteristics of the fracture surface. Two distinct zones with strongly different roughness were observed (Fig. 5): zone I of the size ~ 100-300 μm, depending on testing material in the vicinity of the crack origin has high fracture surface roughness, which corresponds to the area of defect initiation and accumulation during cyclic loading; zone II that covers rest of the fracture surface is smoother than the first, corresponds to the crack propagation according Paris law (1). These results confirm the crack initiation mechanism described in [7].

To investigate scale-invariant properties of the fracture surface, one-dimensional profiles with different lengths were analyzed using two-dimensional profiles with the interferometer New View data (Fig.2).

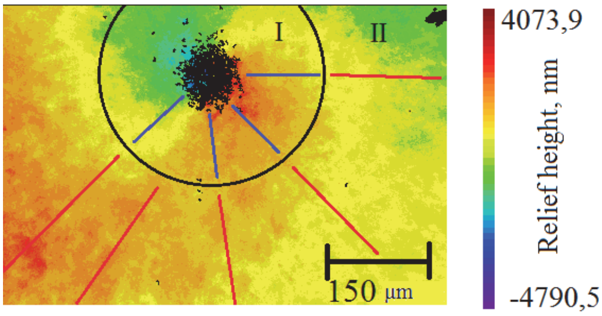


Figure 5: Image of the fatigue crack origin in cylindrical samples (Ti6Al4V) by interferometer New View 2-D. Marked zones I and II are the areas of crack initiation and propagation, respectively. Solid lines are cross-sections of surface roughness used for the estimation of scale invariance (the Hurst exponent)

The Hurst exponent was defined from the slope of linear portion of the correlation function K(r) in logarithmic coordinates [4, 9-10]:

$$C(r) = \left\langle (z(x+r) - z(x))^2 \right\rangle_x^{1/2} \propto r^H \quad (3)$$

where z (x) is the relief height, depending on the coordinate x; angular brackets denote averaging over x, H is the Hurst exponent. In logarithmic coordinates the slope of the linear plot of this function determines the Hurst exponent. The spatial range of linear part establishes the correlated behaviour of defect induced roughness in the direction of fatigue crack propagation.

The influence of the window size (image resolution) on the value of Hurst exponent was investigated by analysing the fracture surface with different resolution from 2.5 µm and 0.1 µm per pixel respectively. Starting from the resolution 0.3 µm by 1 pixel and larger, the value of the Hurst exponent remains practically constant (fig.6). In that case all calculation was carried out on images with 0.5 microns per pixel resolution.

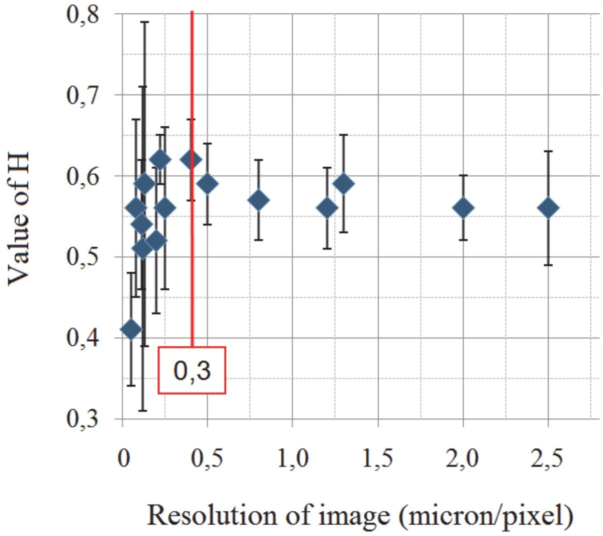


Figure 6: Value of Hurst exponent versus resolution of image.

The correlation function (3) calculated from the profiles for both zones has two linear portions with a break on the scale, which corresponds to change in the mechanisms of fracture surface topography. Whereas functions (2) calculated separately for zones 1 and 2 reveal only one linear portion for each zone (Fig. 7).

The gigacycle fatigue cracks for titanium Grade 4 were originated near the surface (70-150 µm) and the crack hotspot generally could not be detected based on the optical image. The roughness pattern analyzed according to the New View data allows one to differentiate between the zones of crack origination (size ~ 100 µm) characterized by roughness invariance and the rest of the crack propagation roughness zone.

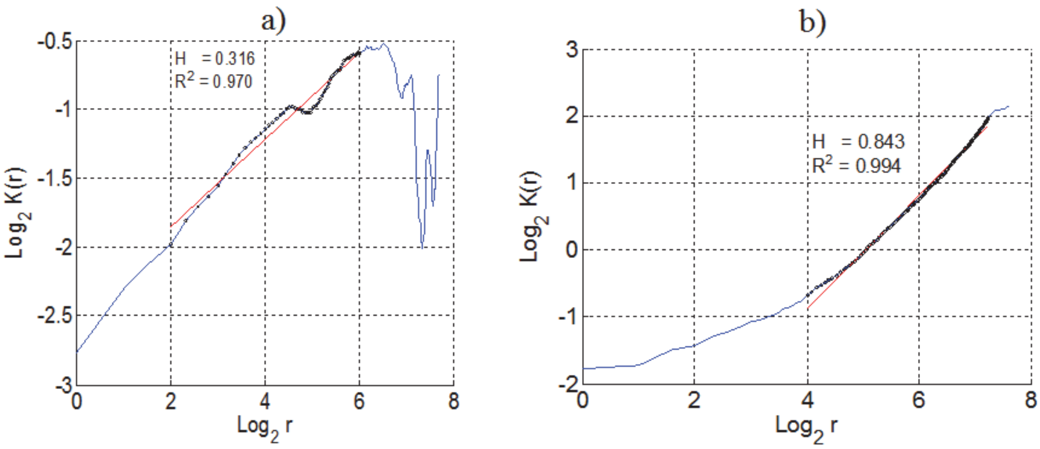
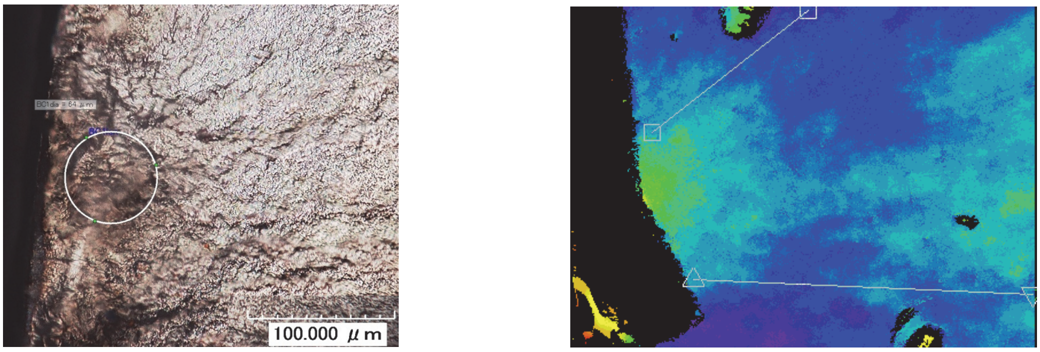


Figure 7: Correlation function built on profiles: a) inside zone 1; b) inside zone 2.

In samples of pure titanium Grade-4 under gigacycle fatigue regime of loading the crack was initiated at a depth of 70-150 µm below the surface. Whereas characteristic feature of the fracture surface of such images unlike the alloy Ti6Al4V is the lack of an optical image of any zone boundaries (Fig. 8,a). However, at the height map obtained using profilometer New View 5010 (Fig.8,b) we can observe the characteristic crack initiation zone, which roughness is different from the rest of the zone of crack propagation, its radius is about to 50 microns.



a) b)

Figure 8: Fracture surface of Ti Grade-4 a)-optical image, b) New View image.

Roughness of fracture surfaces of samples with the surface fatigue crack (Fig. 9) was also investigated by interferometer New View 5010 and analyzed with correlation function (3). The correlation function detects only one slope across the fracture surface of both near and far from the crack initiation point. The value of the Hurst exponent calculated on linear part of the correlation function corresponds to the fractal dimension of the profile of the crack propagating through Paris law like in second zone in previous case. The accumulation defects zone typical to internal crack initiation is not detected. This shows fundamentally different mechanisms for the fatigue crack initiation in the bulk and on the surface of material.

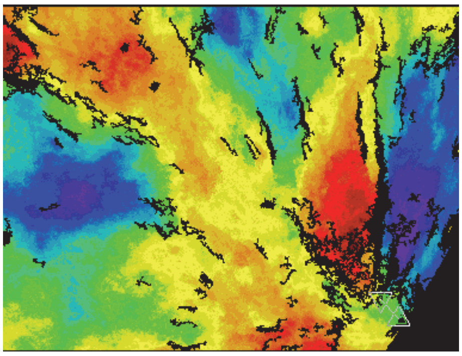


Figure 9: New view image of 2D- profile fracture surface of Ti Grade-4 with fatigue crack initiated from surface of the specimen.

CONCLUSIONS

The analysis of scale-invariant properties of fracture surface allowed us to establish the qualitative difference in terms of the scale invariance (the Hurst exponent) of the surface roughness for the areas of crack initiation and propagation. The crack initiation area can be identified as the zone with pronounced multiscale defect interaction providing correlated behaviour over characteristic scale. The size of this zone and collective defect growth kinetics were studied in [10] and associated with special type of spatial-temporal defect organization named as collective blow-up mode of defects. The scenarios of crack nucleation (in the bulk of specimen for gigacycle load and at the surface for HCF) reflect qualitative different kinetics of collective behaviour of defects in mentioned regimes caused by typical size of defects and interaction length. However, the scenario of crack propagation under gigacycle regime corresponds to the Paris law that reflects the similarity in the mechanisms of plastic flow at the crack tip that still follows the stress induced singularity in term of the stress intensity factor increment.

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REFERENCES

[1] Luong, M. P., Infrared thermographics scanning of fatigue in metals, Nuclear Engineering and Design., 158 (1995) 363-376.

[2] Bathias, C., Piezoelectric fatigue testing machines and devices, International Journal of Fatigue, 28 (2006) 1438-445.

[3] Barenblatt, G.I., Scaling Phenomena in Fatigue and Fracture, International Journal of Fracture, 138(1) (2004) 19-35.

[4] Bouchaud, E., Scaling properties of cracks, J. Phys.: Condens. Matter., 9 (1997) 4319–4344.

[5] Oborin, V.A., Bannikov, M.V., Naimark, O.B., Palin-Luc, T., Scale invariance of fatigue crack grow in gigacycle loading, Technical Physics Letters., 36(22) (2010) 76-82.

[6] Bathias, C., Paris, P.C., Gigacycle Fatigue in Mechanical Practice, Marcel Dekker Publisher Co, (2005).

[7] Sakai, T., Review and Prospects for Current Studies on High Cycle Fatigue of Metallic Materials for Machine Structural Use, Jour. Solid Mech. and Mat. Eng., 3(3) (2009) 425-439.

[8] Cherepanov, G.P., Mechanics of brittle fracture / Moscow, «Nauka», (1974) 640, in Russian.

[9] Ritchie, R.O., Incomplete self-similarity and fatigue-crack growth, International Journal of Fracture, 132(3) (2005) 197-203.

[10] Oborin, V., Bannikov, M., Naimark, O., Froustey, C., Long Range Correlation Large Scale Interactions in Ensembles of Defects: Estimating Reliability of Aluminum Alloys under Dynamic Cycling and Fatigue Loading Conditions, Technical Physics Letters, 37(3) (2011) 241–243.