Study of Temperature Evolution Caused by Mesodefect Kinetics in Metals under Fatigue Loading

Oleg Plekhov[1,a], Oleg Naimark[1,b]

[1] Laboratory Physical Foundation of strength, Institute of continuous media mechanics RAS,

614013 Perm, 1 Ak. Korolev str., Russia

[a] poa@icmm.ru, [b] naimark@icmm.ru

Keywords: infrared thermograthy, defect evolution, fatigue, fatigue crack.

Abstract. The experimental investigation of thermal behavior of titanium alloys under cyclic loading based on infrared thermography (IR camera FLIR SC 5000 with thermal resolution up to 0.1 mK and maximum framing rate up to 500Hz) is carried out. The damage evolution during self-heating test and crack propagation under fatigue loading are studied. It is shown that grain size has a great influence on dissipation process in metals and submicrocrystalline grains qualitatively change the result of self-heating test. The application of IR technique to the fatigue crack propagation study allows us also to investigate the asymptotes of temperature distribution into fatigue crack tip and propose the algorithms to calculate the heat dissipation into crack tip and estimate stress intensity factor.

Introduction

Heat dissipation caused by the mesodefect evolution in metals under cyclic deformation is the subject of intensive research over the period of the last few decades. At present, it is well known that in materials under cyclic deformation, fatigue cracks are initiated in the area of plastic deformation localization and lead to an intensive heat dissipation.

Infrared thermography can be considered as an universal experimental tool for studying thermodynamics of the defect evolution in metals under plastic deformation and failure [1-6]. The application of this technique allows one to detect the time of the fatigue crack initiation and obtain detailed information about the process of its propagation [7,8].

In this work the advantage of this technique is demonstrated by investigation of two problems of fatigue mechanics: application of self-heating test (Resitano technique) to the determination of fatigue limit of submicrocrystalline metals and verification of linear fracture mechanics formulae to the investigation of temperature distribution in fatigue crack tip.

Our experimental investigation used an IR camera FLIR SC 5000 (thermal resolution up to 0.1 mK and maximum framing rate up to 500Hz in full frame) shows that the appearance of mesodefect structures lead to the complex thermal behavior.

The self-heating test is generally used for the fast determination of fatigue limit of polycrystalline metals. According to the main idea of this technique the transition through the fatigue limit is accompanied by microplasticity and, as consequence, changing of temperature kinetics and heat radiation of the specimen. During the test the applied stress amplitude was increased after each 30000 cycles on 10 MPa.

Other promising application of infrared thermography is the study of crack propagation. This technique allows one to measure, in real time, the fundamental parameters of fracture mechanics (for instance stress intensity factor). Based on this technique we investigate the asymptotes of temperature distribution at fatigue crack tip and propose the algorithms to calculate the heat dissipation into crack tip and estimate stress intensity factor (SIF).

Material and experimental conditions

The samples of titanium Grade 2 were manufactured by the method of intensive plastic deformation [9] and had the grain size of about 150 nanometers. The mechanical properties of titanium Grade 2 in polycrystalline and submicrocrystalline state are presented in Table 1. The geometry of samples is represented in figure 1. The cyclic loading was carried out using a resonant electrodynamic testing machine Vibrophore Amsler providing uniaxial loading with the prescribed boundary conditions for stress. The resonance frequency of the sample was 76 Hz.

The experimental procedure corresponded to the express infrared techniques for determination of the fatigue limit [5,6]. This technique is based on the hypothesis about correlation of the value of the fatigue limit with the threshold of structural evolution. After passing the fatigue limit (loading with stress amplitude higher than the fatigue limit) an intensive structural evolution and, as a result, an intensive temperature rise was observed in the specimens. The fatigue history of each sample including "cyclic" blocks contained 30000 cycles, with the asymmetry factor of a cycle equaling 0.1.

Table 1. Mechanical properties of titanium Grade 2 at coarse and fine grain states

Type of treatment	tensile strength,σ_B, (MPA)	yield stress, $\sigma_{0.2}$, (MPa)	ultimate elongation, (δ,%)
Initial coarse grain state (grain size 25 μm)	440	370	38
IPD + hot rolling (grain size 0.3 μm)	1090 ± 20	980 ± 20	13 ± 1

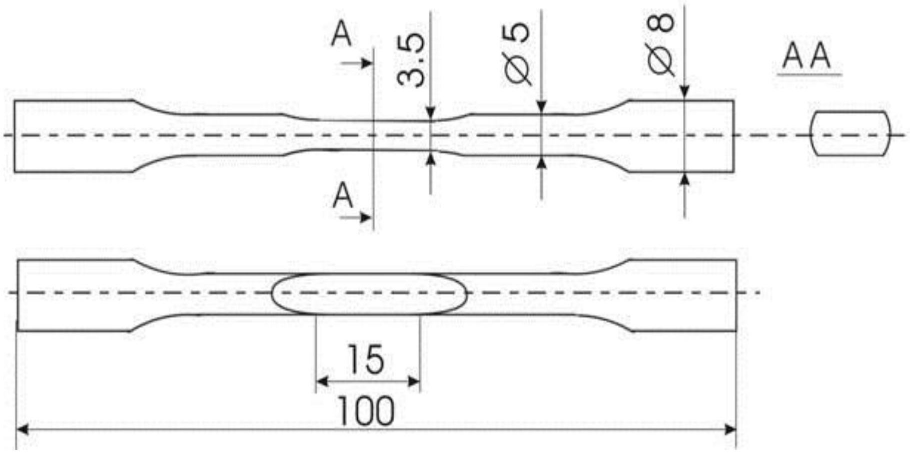


Fig. 1 Geometry of samples used for self-heating tests. The sizes of a gage part of a sample 15x5x3,5 mm.

For each subsequent block the average stress was increased by 10 MPa. At each step of loading a temperature rise in the sample was measured. Between cycles the samples were unloaded and relaxed until they reached thermal equilibrium with the environment.

To study the temperature evolution at fatigue crack tip we used the plate specimen presented in figure 2. The specimens were manufactured from a commercial purity titanium sheet 3 mm thick. The geometry specimen is shown in figure 2.

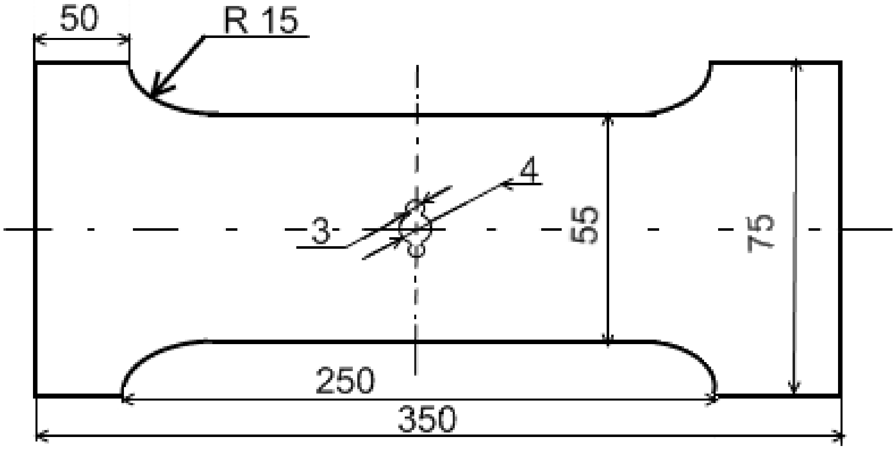


Fig. 2. Specimen geometries for investigation of temperature evolution under fatigue crack propagation.

Fatigue crack propagation tests were carried out using 100 kN servo-hydraulic machine Bi-00-100. The strain was measured by an axial extensometer - Bi-06-304 with an accuracy of ± 1,5 mm.

To study thermal effects at the crack tip, the specimen was pre-weakened by holes (Fig. 2). The fatigue crack (about 10 mm) was initiated at the initial stage of the experiment by high amplitude cyclic loading of the specimens at the average stress of 215MPa, stress amplitude of 238 MPa and loading frequency of 20 Hz. Then the load was decreased to slow down the rate of crack propagation, which allows us to perform detailed analysis of the heat generation processes at the crack tip.

The surface of the specimens was polished in several stages by the abrasive paper (at the final stage of polishing the grit size does not exceed 3 μm). Before starting the experiment, the polished surface was covered by a thin layer of amorphous carbon.

The temperature evolution was recorded by the infrared camera FLIR SC 5000 (thermal resolution up to 0.1 mK and maximum framing rate up to 500Hz in full frame) at the frequencies ranging from 350 to 950 Hz and a minimum spatial resolution of $2\cdot10^{-4}$m. Calibration of the camera was made based on the standard calibration table.

Experimental results of damage evolution study

Figure 3 presents the results of experiments. The polycrystalline titanium shows nonlinear two-step growth of heat dissipation. According to the used technique the point of crossing of straight lines in figure 3 determines the value of the fatigue limit for the coarse-grained titanium (the average stress is 80 MPa, the maximal stress is 145 MPa).

The Experiment with the coarse-grained titanium was stopped before failure in the case when the sample temperature overran a working range of the camera with exposition 1100 μsec (75 ^{o}C).

The results of infrared scanning of submicrocrystaline titanium show that cyclic loading is accompanied by a qualitative change in the mechanisms of dissipation. At small stress amplitudes the average temperature of the sample with a fine grain structure insignificantly exceeds the temperature of the coarse-grained titanium sample. At the stress of about the fatigue limit the picture qualitatively changes. For the stress higher than the fatigue limit of the coarse-grained titanium the increment of temperature in the submicrocrystalline sample is much less than in the samples in a polycrystalline state. A linear dependence of the temperature growth rate on the average stress was observed for all fatigue histories of submicrocrystalline samples.

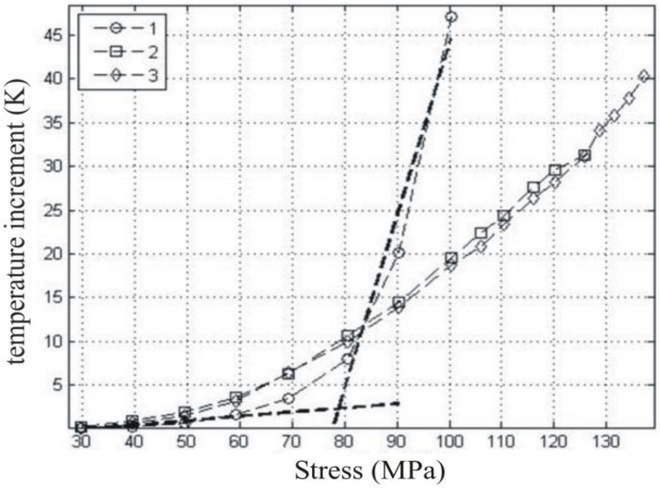


Fig. 3. Mean temperature increment of titanium samples in coarse-grained (curve 1) and submicrocrystalline states (curves 2,3) versus mean stress; dashed lines determine approximately the value of fatigue limit (the stress corresponding to the knee point).

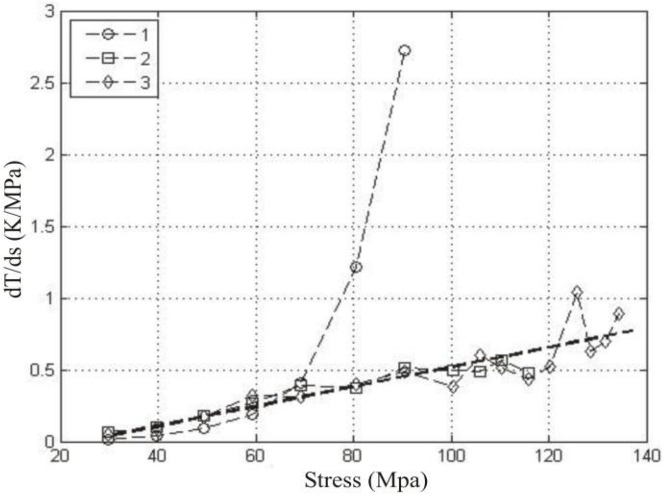


Fig. 4. The plot of mean temperature growth rate versus mean stress for coarse-grained (curve 1) and nanocrystalline titanium (curves 2,3); dashed line denotes linear approximation of curves 2,3.

The temperature of samples is stabilized approximately after 20000 cycles which reflects the ability of the samples with submicrocrystalline structure to form an equilibrium defect system (probably grain boundary defects) and qualitatively confirms the theoretical result about the formation of defect "lattice", whose characteristic size (density of dislocation) homogeneously increases with increase in the average stress.

Submicrocrystalline samples during cyclic loading experienced brittle failure, which occurred at the stress amplitude 35 % - 40 % higher than in titanium samples in an ordinary polycrystalline state.

Experimental results of crack propagation study

Figure 5 shows the evolution of the maximum temperature, specific heat power and stress at the crack tip in the process of loading (220 MPa stress amplitude, mean stress of 212 MPa and a frequency of 10 Hz). The indications of the displacement sensor (don`t plotted in fig.5) mounted at different crack edges clearly demonstrate that the crack opening varies in phase with the applied stress.

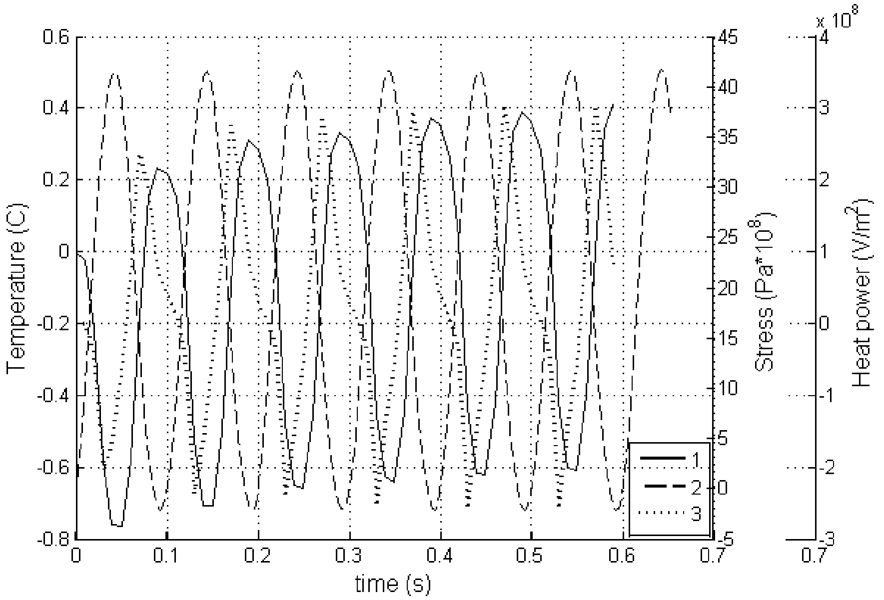
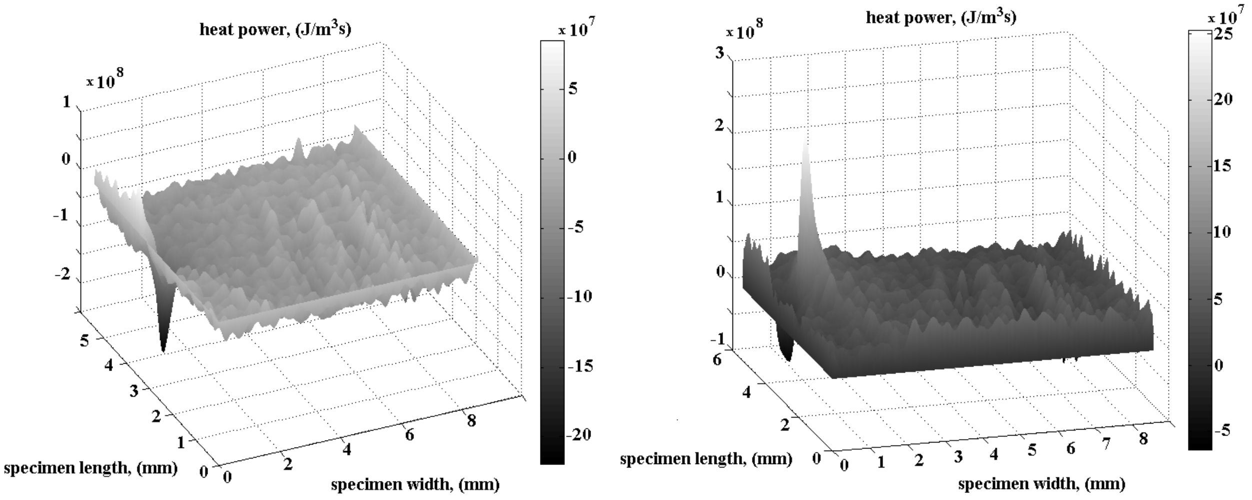


Figure 5. Evolution of maximum temperature at the fatigue crack tip (1), stress (2), and specific heat power (3) under cyclic deformation.



a) b)

Fig. 6. Specific heat power distributions on the specimen surface at different times. Thermo elastic (a) and thermoplastic (b) effects at crack tip.

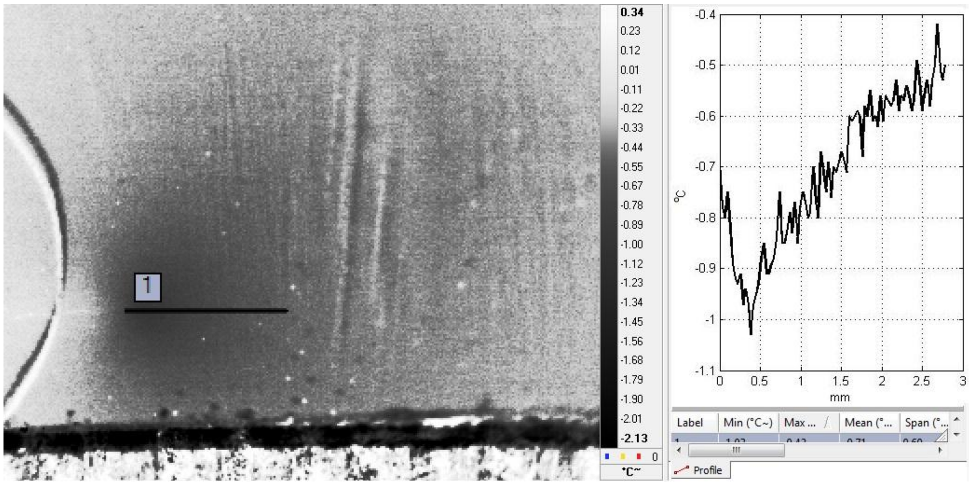
The analysis of the data presented in Fig.5 shows that the maximum applied stress and the maximum intensity of heat dissipation at the tip of the fatigue cracks do not coincide in time.

To determine a specific heat power at the crack tip the corresponding algorithms including data filtration, movement compensation and a solution of inverse problem were developed. As a result a temperature field can be automatically converted in field of specific heat power. Figure 6 presents the spatial heat sources distributions on specimen surface in different time moments corresponding to the different stress levels.

To calculate the value of SIF we analyzed the low-temperature (thermoelastic) zone at the crack tip. The theoretical value of SIF can be calculated as follows:

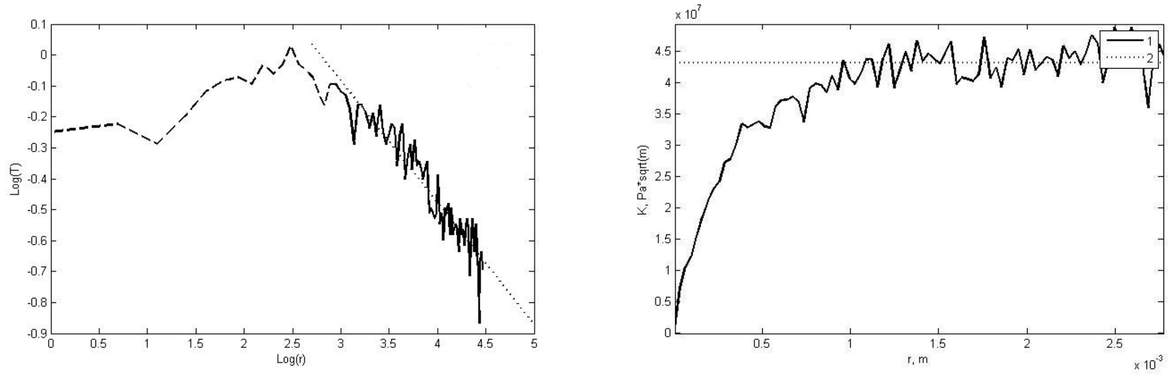
$$K = \sigma\sqrt{\pi a}F(\alpha), \qquad (1)$$

where σ is the applied stress, a is half of the crack length, $\alpha = 2a/W$, W is the specimen width, $F(\alpha) = \left(1 - 0.025\alpha^2 + 0.06\alpha^4\right)\sqrt{\sec(\alpha\pi/2)}$.



a) b)

Figure 7. Temperature distribution over the specimen surface at the fatigue crack tip (a), temperature increment in the direction of crack propagation (b).



a) b)

Figure 8. Temperature increment in the direction of crack propagation in log-log coordinates (a), variation of SIF with the distance from visually determined crack tip (b, horizontal line is the theoretical value of SIF).

To determine experimentally the value of SIF we can use the well known relation of thermoelasticity

$$\Delta\sigma = -\frac{\rho c}{\beta T_0}\Delta T, \tag{2}$$

where ρ is the material density, β is the thermal expansion coefficient, c is heat capacity, ΔT is experimentally determined temperature increment near the fatigue crack tip.

Let us to consider the one-dimensional function $\Delta T(r)$ determined in the direction of crack propagation (Fig 7). First, it is necessary to determine the location of the crack tip. The crack and flat specimen surface have different emissivity and crack can be easily visualized by infrared thermography. However, the existence of the cohesive force zone into the crack tip complicates the problem. This zone cannot be easily observed. Let us assume that the maximum stress corresponds to the real crack tip position. In this case, we can associate the location of minimum temperature increment with the real position of the crack tip.

Based on equation (2) we can calculate the stress increments in the direction of crack propagation $\Delta\sigma(r) = -\frac{\rho c}{\beta T_0}\Delta T(r)$, which can be related with SIF

$$\Delta K = \Delta\sigma(r)\sqrt{\frac{\pi r}{2}} = -\frac{\rho c}{\beta T_0}\Delta T(r). \tag{3}$$

An example of applying equation (3) for infrared monitoring data is presented in figure 8. A slope of the last part of the plot is close to a theoretically determined value 0.5. The first part of the plot can be considered as the result of the appearance of the cohesive force zone at the crack tip. The last part of the plot gives the constant value of SIF, which coincides with value determined by equation (1).

Figure 9 presents the comparative analysis of theoretically calculated and experimentally determined values of SIF.

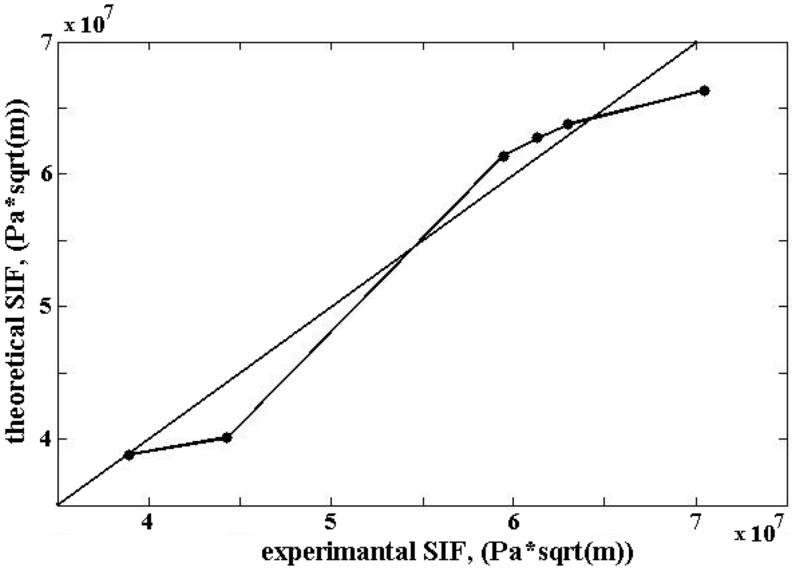


Fig. 9. Correlation of theoretically calculated and experimentally determined values of SIF.

The analysis of data presented in figure 9 shows a good agreement of experimental and theoretical results. It is necessary to note that the good agreement was obtained for relatively small stress amplitude only. The preliminary attempts (don`t presented in the framework of this paper) to calculate the value of J-integral based on the HHR-solution for stress distribution at crack tip gives significantly poorer results.

Conclusion

The self-heating test shows the effect of grain size on the energy dissipation process in titanium. The polycrystalline titanium exhibits an ordinary behavior. The temperature rises sharply after transition through fatigue limit. The temperature kinetics versus stress amplitude in submicrocrystalline titan is linear up to specimen failure. This fact allows us to conclude that submicrocrystalline titan which is characterized by specific state of ensemble of grain-boundary defects has a unique structural mechanism for energy dissipation and can use this mechanism at both small and high stress amplitude.

The study of the thermoplastic effect at the fatigue crack tip has shown that the process of heat dissipation is essentially nonlinear. At this stage of research the results of experimental study suggest that the maximum heat is reached on the descending branch of the load.

The preliminary attempts to calculate the value of J-integral based on the HHR-solution for stress distribution at crack tip gives unsatisfactory results. The good precision in the calculation of SIF can be considered based on the thermoelasticity theory for relatively small stress amplitude.

Acknowledgement

Work is partially supported by grant of the Russian Fund for Basic Research 11-01-00153, and grant МД-2684.2012.1.

References

[1] O. Plekhov, T. Palin-Luc, O. Naimark, Uvarov S. and N. Saintier: Fatigue and fracture of engineering materials and structures Vol. 28 (2005), p. 169

[2] P. Rosakis, A.J. Rosakis, G. Ravichandran, J. Hodowany: J. Mech. and Phys. Solids, Vol. 48, (2000) p. 581

[3] W. Oliferuk, M. Maj, B. Raniecki: Materials Science and Engineering A, Vol. 374 (2004) p.77

[4] M. Poncelet, C. Doudard, S. Calloh, B. Weber, F. Hild: J. Mech. and Phys. Solids Vol. **58** (2010) p. 578

[5] G. Fragione, A. Geraci, G. La Rosa, A. Risitano: Int. J. Fatigue Vol 24 (2002) p.11

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

[7] N. Ogasawara, M. Shiratori: SPIE proceeding series Vol. 3056 (1997) p.201

[8] R. Jones, M. Krishnapillai, K. Cairns and N. Matthews: Fatigue and Fracture of Engineering Materials and Structure Vol. 33 (2010) p.871

[9] V. Latysh, I. Semenova, G. Salimgareeva, I. Kandarov, Y. Zhu, T. Lowe, R. Valiev: Mater. Sci. Forum Vol. 503-504 (2006) p. 763