Study of Stored Energy Evolution at Fatigue Crack Tip Based on Infrared Data

Anastasia Fedorova[*1], **Michael Bannikov**[1], **Oleg Plekhov**[1]

[1]Institute of continuous media mechanics Russian academy of science, 614013, Perm, Russia
*anastfed@mail.ru

Abstract The presented work is devoted to the experimental study of heat dissipation process caused by fatigue crack propagation. To investigate a spatial and time temperature evolution at the crack tip, set of experiments has been carried out using plate titanium specimens with pre-grown centered fatigue crack. An original mathematical algorithm for experimental data treatment has been developed to obtain a power of heat dissipation caused by plastic deformation at the crack tip. The algorithm includes spatial-time filtration and relative motion compensation procedures. The time dependence of the stored energy was calculated as difference between work caused by plastic deformation near the crack tip and heat dissipation energy obtained from experimental data. As a result, it has been shown that the stored energy has to accumulated during the fatigue test and has to be equal to zero when the crack reaches the critical length corresponding to the sample failure.

Keywords stored energy, plastic work, fatigue test, heat dissipation, infrared thermography

1. Introduction

Infrared thermography is the simple way to measure the temperature of surface and to monitor of crack propagation during cycling test. It is well know that the changing of the temperature correlates to the physical processes of damage and failures in metals [1]. The application of infrared thermography as a non-destructive method to detect the damage accumulation and to investigate the fatigue process of materials has become popular and has been wildly investigated in literature in last 25 years.
In materials under cyclic deformation, fatigue cracks are initiated in the area of plastic deformation localization and lead to an intensive heat dissipation [2]. Investigation of the heat dissipative and absorption laws can take information about dissipative ability of material and current state of structural evolution.
This work is devoted to investigation the time evolution of the stored energy during fatigue test using infrared technique and specially developed methods of data processing. Proposed approach allows us to measure parts of plastic work that dissipated as heat and stored in metals at fatigue crack tip. Study of these tasks enables to obtain information about the evolution laws describing the irreversibility of the fatigue process.

2. Materials and conditions of experiments

Experimental study of temperature evolution at the fatigue crack tip was carried out on the plane specimens of titanium Ti-4.2Al-1.6Mn. The specimens were manufactured from a commercial titanium sheet 3 mm thick.
Mechanical properties of material are modulus of elasticity - 64 GPa, yield stress - 800 MPa, ultimate stress 900 MPa, fatigue limit (R=-0.051) – 460 MPa, fracture toughness – 75.6 MPa$\sqrt{m}$.
The geometry of specimen is shown in Fig. 1. The specimens were weakened by holes to initiate fatigue crack at the specimen center. 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 a 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 infrared camera CEDIP Silver 450M. The spectral range of the camera is 3-5 mm. The maximum frame size is 320×256 pixels; the spatial resolution is 10^{-4} meters. The temperature sensitivity is 25 mK at 300 K. Calibration of the camera was made based on the standard calibration table.
Mechanical tests were carried out at 100 kN servo-hydraulic machine Bi-00-100. The test conditions comply with the conditions of the experiment was described in [3]. The process of crack propagation was studied at 5 Hz loading frequency.
The selected frequency of loading provides a close to adiabatically condition at crack tip. At low frequency (less that 5 Hz) the heat transfer process plays a great role and doesn't allow one to calculate the right value of heat source. The investigation of high loading frequency requests the high frame rate and treatment of large amount of infrared data.

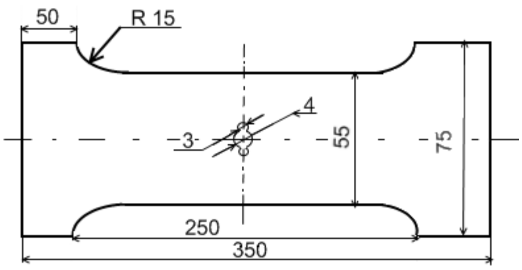
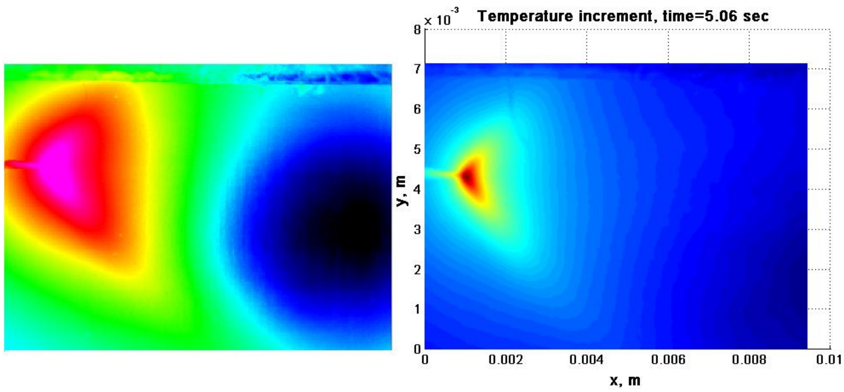


Figure 1. Geometry of sample (all sizes are in millimeters).

3. Experimental data processing and determination of the stored energy

At the beginning of data processing procedure, the first frame was subtracted from the film to eliminate the influence of infrared radiation from the camera lens on the determined temperature field. Due to the relative motion of the specimen and infrared camera lens under cyclic tests, there is the problem of motion compensation in order to obtain the correct temperature data at a given point on specimen surface. Compensation of relative motion was made based on the algorithm described in details in [4]. The main idea of this algorithm is the selection of marker-zone on the studied surface and searching this area on the surface in each next time step. Farther, displacement of each point on the surface is calculated for each time step. As a result of data processing, we obtained the temperature increment field (Fig. 2) based on which the heat sources field was determined.



A **B**

Figure 2. Infrared image of sample before data processing (A) and obtained temperature increment field (B).

To calculate the specific power of the heat source, we have used a finite difference scheme of the equation for heat sources evolution (Eq. 1).

$$s = \rho c\left(\dot{T} + \frac{T}{\tau}\right) - k\Delta T, \tag{1}$$

where T – temperature, ρ – density (4550 kg/m^3), c – heat capacity (600 J/(kg·K)), k – heat conductivity (6.5 W/(m·K)), s – unknown specific power of the heat source (W/m^3), τ – a constant related to the losses of heat by heat exchange with the surroundings (10^3 J/(m^3·K)).

The heat power of sources close to fracture moment (at 5.06 sec after beginning of the last stage of test) is shown in Fig. 3. At the last moments before fracture, we can observe pronounced plastic deformation at crack tip and plastic zone has a “butterfly form” near the crack tip as it is presented in Fig. 3.

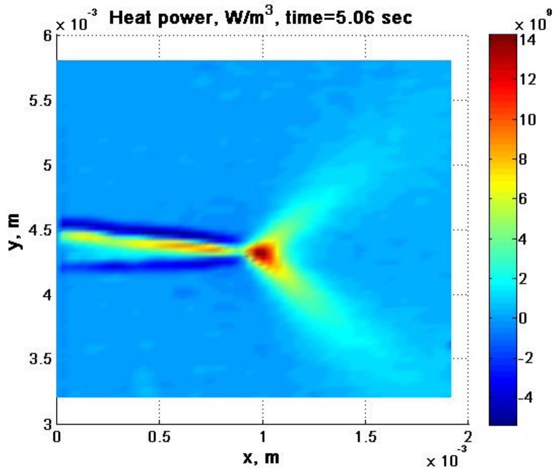


Figure 3. Experimental data of heat power field near the crack tip at the beginning of unstable crack propagation.

Taking into account assumption from [5, 6], we also suppose that some of the irreversible plastic work contributes to heat generation while the rest is stored as energy of crystal defects accompanying plastic deformation, traditionally known as the stored energy of cold work.

To define the plastic work near the crack tip we used the solution for stress distribution at crack tip obtained by Hutchinson, Rice and Rosengren (HRR-solution). Specific plastic work in the direction of crack propagation can be written as [7]:

$$w_p(x,t) = \int_0^{\varepsilon_p} \sigma d\varepsilon = \frac{n}{n+1}\frac{J(t)\sigma_e^{n+1}}{I_n x}, \tag{2}$$

where n – hardening coefficient (in our case n=4), I_n – function of hardening coefficient, x – distance from the crack tip, σ_e – tabulation function, $J(t)$ – energy J-integral that is the function of applied cycling loading and crack length. Time dependence of J-integral is presented in Fig. 4.

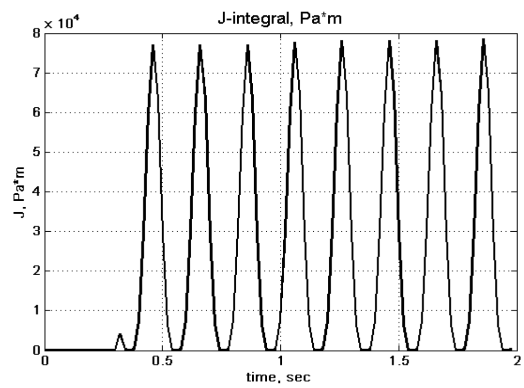


Figure 4. Time dependence of energy J-integral during cycling loading.

The stored energy was obtained as difference between accumulated plastic work (Eq. 3) and accumulated heat dissipation energy (Eq. 4) calculated at the point of the crack tip x_0 during all time moments of experiment as follows:

$$W_p(t) = \int_0^{t_i} w_p(x_0, t)dt \tag{3}$$

$$Q(t) = \int_0^{t_i} s(x_0, t)dt \tag{4}$$

The time dependence of accumulated plastic work, dissipative energy and stored energy that was calculated at the moving fatigue crack tip is shown in Fig. 5. Comparing time evolution of the plastic work and dissipative energy, the deformation process during cycling loading can be divided into three parts. The first one is about 1.3 seconds when two curves have a good correlation that can be connected with thermoelastic effect and existence the elastic part of the mechanical work.

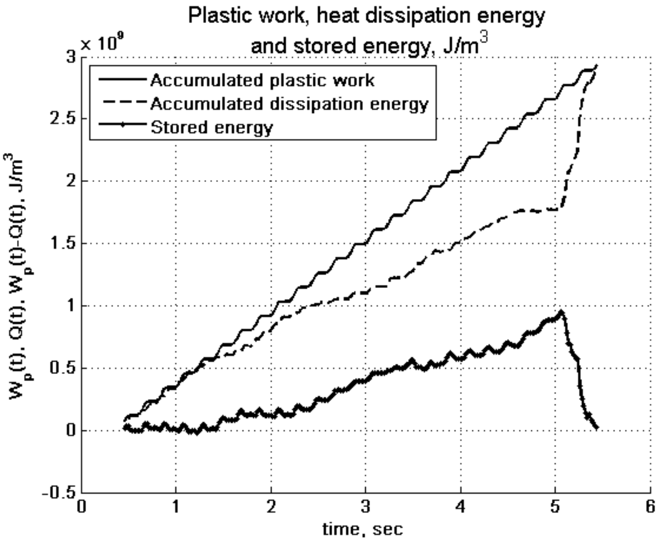


Figure 5. Time dependence of plastic work, heat dissipation energy and stored energy.

From 1.3 second to 5 second, dissipation energy increases slower than plastic work. In this period stored energy is monotonically accumulated in deformed material and spent on the potential energy of lattice distortion. At the last moments before fracture the heat dissipation energy increases explosively and reaches the value of the plastic work. The stored energy aims to the zero and material goes to the fracture stage when macroscopic displacements play important role and it is accompanied significant energy dissipation.

Data obtained for studied material displays that value of the stored energy increases to a critical point after that all mechanical energy goes to the heat and stored energy decreases explosively to zero, which ultimately leads to the destruction.

4. Conclusion

The effect of heat dissipation at the crack tip under cyclic loading has been studied based on the infrared thermography. To calculate the values of heat dissipation at crack tip an original data processing algorithms were applied. The algorithms include the relative motion compensation and spatial-time filtration procedures. As a result of infrared data treatment we determine the characteristics associated with the heat dissipation processes at the crack tip, which allowed us to propose method for determining the current values of the heat dissipation energy and stored energy

during cycling loading.
As a result, it has been shown that the value of the stored energy has to accumulate during the fatigue test and has to be equal to zero when the crack reaches the critical length corresponding to the sample failure. So, it can be used as a criterion for prediction of damage.
The set of developed mathematical algorithms and methods of the experiment allows us to develop in a future engineering methods for analyzing the current crack state inside of real constructions in a wide range of applied loads.

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References

[1] X.D. Li, H. Zhang, D.L. Wu, X. Liu, J.Y. Liu, Adopting lock-in infrared thermography technique for rapid determination of fatigue limit of aluminum alloy riveted component and affection to determined result caused by initial stress. Int J Fatigue, 36 (2012) 18-23.
[2] A.A. Shanyavskiy, Bezopasnoe ustalostnoe razrushenie elementov aviakonstrukcii. Sinergetika v ingenernih prilogeniyah [Safe fatigue damage of aircraft construction elements. Synergetics in engineering applications]. Ufa, (2003) 803.
[3] M. Bannikov, A. Terekhina, O. Plekhov, Vestnik Permskogo gosudarstvennogo tehnicheskogo universiteta. Mehanika, 2 (2011) 14.
[4] A.Yu. Fedorova, M.V. Bannikov, O.A. Plekhov, Infrared thermography study of the fatigue crack propagation. Fracture and Structural Integrity, 21 (2012) 46-53.
[5] J.Hodowany, G. Ravichandran, A.J. Rosakis and P.Rosakis, Partition of plastic work into heat and stored energy in metals. Exp Mech, 40(2) (2000) 113-123.
[6] O. Plekhov, S. Uvarov, O. Naimark, Theoretical and experimental investigation of dissipated and stored energy ratio in iron under quasi-static and cyclic loading. Strength of materials, 1(391) (2008) 101-105.
[7] Yu.G. Matvienko, V.G. Avramenko, Dynamics of temperature field in the plastically deformed metal. II. Specimen with a crack. Deformation and fracture of materials, 10 (2009) 2-10.