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Development of the measurement system for determination of energy dissipation power at fatigue crack tip

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Abstract

The heat dissipation process caused by propagating fatigue crack in AISE 304 steel was studied. To calibrate the heat dissipation data and to implement the precise measurement of heat flow the infrared camera was combined with original measurement systems based on Pelteir element and potential drop technique. The developed experimental setup allows us to monitor the heat flow, heat sources distribution and crack length during the experiment. As a result of the study we have shown the linear dependence between rate of fatigue crack growth and energy dissipation rate at the fatigue crack tip.

1. Introduction

The process of fatigue crack propagation in metals can be divided into three basic regimes [1]. The threshold regime is characterised by low crack rate and strong effect of materials structure on the crack dynamics. At the second regime the crack propagates to 10E-8 – 10E-3 meters per one cycle. Material structure has little effect on fatigue crack rate at this exponential regime. The last regime is regime of fast (unstable) crack growth. The structure of material has again a strong influence on the peculiarities of crack kinetics.

A large number of studies were directed to the explanation of fatigue crack propagation in exponential regime. This regime is most common in many practical situations. The crack propagation in exponential regime can be described based on the Paris's law. This law can be considered as a generalization of huge amount of experimental data within framework of linear fracture mechanics [2].

Paris`s law can be written as follows

$$\frac{da}{dN} = C \cdot \Delta K^m, \qquad (1)$$

where a – crack length, $\Delta K = \Delta\sigma\sqrt{\pi a}Y(a, W)$ – stress intensity factor, σ – applied stress, Y – function of specimens geometry and crack length, C,m – empiric constants, N – number of cycles.

At present time there are many modifications and generalizations of Paris's law. They allow one to describe the effects of asymmetry of loading cycle, crack roughness, plastic deformation at crack tip on the crack dynamics.

Considerable attention has been paid for description of exponential regime based on the other characteristics of the process, distinct from the stress intensity factor which doesn't take into consideration the process of plastic flow at the crack tip in metals. In 1979, the relation relating the rate of fatigue crack and characteristic size of plastic deformation zone was proposed [3]

$$\frac{da}{dN} = C\Delta CTOD. \qquad (2)$$

The analysis of experimental data allows us to conclude that fatigue crack rate at exponential regime can be presented as a function of crack tip opening displacement, dissipated energy, area of hysteresis loop, characteristic size of plastic zone at crack tip, J-integral and many other parameters.

The effect of the energy dissipation at fatigue crack tip in the terms dissipated power and J-integral was studied in [4]. The basic parameter in this work is the energy U, which equals to a ratio of an area of stress-strain hysteresis loop and unit area of crack surface. Mathematically the energy can be calculated as

$$U = \frac{\int_{-Y_p}^{Y_p}\int_0^{X_p}\left(\int_{\varepsilon_1}^{\varepsilon_2}\sigma_u d\varepsilon - \int_{\varepsilon_1}^{\varepsilon_2}\sigma_l d\varepsilon\right)dXdY}{\frac{da}{dN}}, \qquad (3)$$

where $\varepsilon_1, \varepsilon_2$ – deformation in the extreme points of stress-strain hysteresis loop, σ_u, σ_l - high and low stress at the local hysteresis loop in the plastic zone, X_p, Y_p – size of plastic deformation zone.

In the general case the energy balance of a sample with fatigue crack under cyclic loading we can write as

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$$W' = U' + \Delta J da, \quad (4)$$

where W' - applied power, U' energy accumulated into crack tip process zone, $\Delta J da$ – energy spent during crack propagation to distance da.

The energy balance equation for sample with fatigue crack for one cycle we can obtain if divide left and right parts of equation (4) into da

$$W = U + \Delta J. \quad (5)$$

Almost similar relations for the energy balance in the propagation of cracks were obtained in works [6,7]. Omitting mathematical transformations, the energy balance in the propagation of the crack can be written as:

$$\frac{da}{dN} = \frac{W^p - Q}{\Lambda - J}, \quad (6)$$

where a - crack length, N-number of cycles, W^p - power of plastic work, Q - power of heat dissipation, Λ - the energy expended in the formation of the new surface and the failure of the material in the process zone (all energies are calculated for one complete cycle of deformation) , J - energy J-integral.

The quantities on the right side of equation (6) can be expressed in terms of power of the heat flow. Using Taylor's hypothesis we can write $\beta = \frac{W^p - Q}{W^p}$. In the work of Taylor it has been shown that the quantity (the relative rate of the energy storage) does not exceed several percent. Subsequent experimental and theoretical work has shown that this value is a function of various parameters of the process of plastic deformation [8]. However, for the integral value calculated for the full cycle of deformation, this hypothesis can be accepted as a first approximation.

The resistance of the material to crack propagation (Λ) can be estimated based on critical value of J-integral - J_c [8]. The value of J-integral can be related to the rate of heat generation, for example using the equation of Rice $J \sim \frac{1}{t(l-a)} W^p \sim \frac{1}{t(l-a)\beta} Q$ (where tl - sectional area of sample). As a result, the rate of fatigue crack propagation can be written as

$$\frac{da}{dN} = \frac{(1-\beta)}{\beta} \frac{Q}{(J_c - f(Q))} \quad (7)$$

The value of J-integral grows with increasing of crack length. It leads both to the decrease of denominator in the Rice`s equation and increase of the area of the hysteresis loop (rate of energy dissipation). Consequently, in the first approximation, we can write that in the steady of propagation conditions, rate of fatigue crack propagation is proportional to the product of the energy dissipation rate and the current length of the crack

$$\frac{da}{dN} \sim Qa. \quad (8)$$

Currently, there is a possibility of direct non-contact experimental measurement of the power dissipation at the crack tip based on infrared thermography [8]. There are several technical problems for application of infrared thermography for study of energy balance in solid under crack propagation. The measured temperature signals are noisy and heat exchange process between sample and environment is ill-defined. It leads to low precision in the solution of inverse thermal conductivity problem. The problems can be partly solved by the development of special post processing data filtering procedure and additional experimental measurements of heat exchange law [9].

The principal solution of the problem of energy dissipation measurement under deformation and failure can be reach by the development of additional system for direct monitor of heat flow. This idea was affectively used for investigation of energy dissipation under liquid flow [10]. This work is devoted to extension of this idea and developments the original heat flow measurement technique for study the fatigue problems. To study of heat dissipation under crack propagation we simultaneously applied the infrared thermography and Peltier-based measurement system. The infrared thermography allows us to investigate the spatial distribution of heat sources. The additional Peltier-based system allows us to measure the real value of heat flow and calibrate the infrared measurements.

As a result it was shown that early developed algorithms for calculation of heat sources based on infrared data are valid. The measurement of energy dissipation under crack propagation shows that crack rate at the stable regime of crack propagation is a linear function of energy dissipation rate for metals under investigation.

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2. Experimental setup and experimental conditions

2.1. Experimental setup

Experimental study of temperature evolution at the fatigue crack tip was carried out on the plane samples of stainless steel AISE 304. The sample geometry is presented in figure 1.The samples were manufactured from a commercial steel sheet with a thick of 3 mm. The gauge part of the specimen was 55x200 mm. The peculiarities of experimental conditions and sample preparation are described in [11]. Fatigue experiments are carried out on a servo-hydraulic testing machine Bi 10-00-1. The process of crack propagation was studied at 10 Hz loading frequency and R=-0.027.

The specimens were weakened by holes to initiate fatigue crack at the specimen centre. The fatigue crack (about 10 mm) was initiated at the initial stage of the experiment by high amplitude cyclic loading. Then the load was decreased to slow down the rate of crack propagation. It is allowed one to perform 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 3μm). Before starting the experiment the polished surface was covered by a thin layer of amorphous carbon.

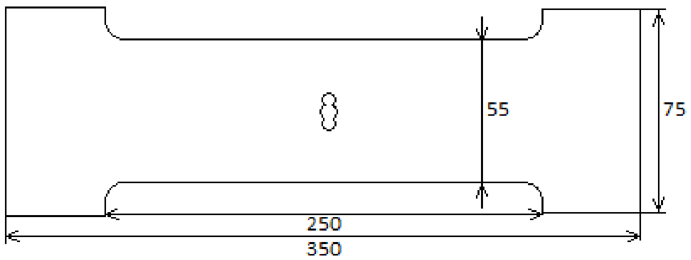

Fig 1. *Specimen's geometry*

The temperature evolution was recorded by infrared camera FLIR SC 5000. The spectral range of the camera is 3-5 μm. 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. It was used FLIR SC5000 MW G1 F/3.0 close-up lens (distortion is less than 0.5%) to investigate the plastic zone in details.

To measure the heat flow near the crack tip the original Peltier-based experimental setup was developed. To control the crack length a measurement system has been developed. The crack length measurement system is based on the potential drop technique. The principal scheme of experiments is presented in figure 2. The following notations are accepted in figure 2:

1. Testing sample;
2. Infrared camera;
3. Peltier element;
4. Potential drop measuring setup to monitor the crack length;
5. Analog amplifier MDU-8;
6. Analog digital converter ADC NI USB-6251;
7. PC with LabView software.

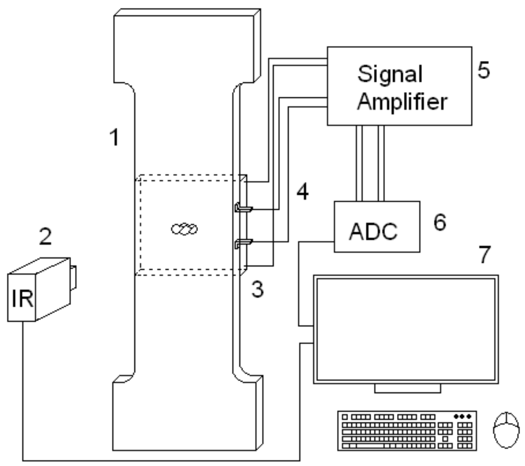

Fig. 2 *Principal scheme of experimental setup.*

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2.2. Measurement length of fatigue crack

The potential drop technique was used to determine the length of the crack. This method implements the continuous monitoring of long crack evolution during fatigue tests. The pair electric contacts were placed on specimen for implementation of the method. The contacts were connected with the sample by welding. The potential drop value was detected between these contacts. Direct current (5 A) was flowed through the sample using grips of the testing machine. The principal scheme of potential drop thechnique is presented in figure 3.

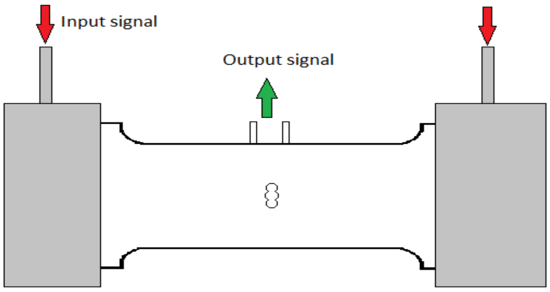

Fig 3. *Scheme of potential drop method*

This value of current was chosen to provide good noise-signal ratio and avoid high sample heating. The signal obtained from the sample was transferred to a differential amplifier and then fed to the analog-digital convertor (ADC). The digitized signal is processed using LabView software. Designed electronic device allows us to monitor crack growth during the fatigue test, as well as estimates of stress intensity factor (SIF). Calibration of an electronic device was made based on the optical microscope data. The calibration plot is shown in figure 4.

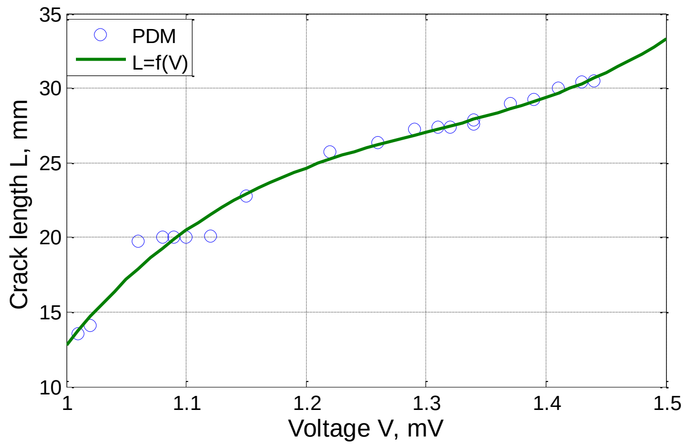

Fig 4. *Calibration graph of potential drop method*

The developed method allows us to measure the length of fatigue crack up to 0.1 mm. Besides, this method is not limited to a visual contact with the sample, whereby the other instrumentation can be using.

2.3. Measurement of heat dissipation

The infrared thermography can be used for directly measurement of heat flow. Any additional numerical methods for processing infrared data lead to an increase in the error of the final result. It increases the importance of direct measurement of heat flux. This problem can be solved based on the the Peltier element.

Peltier effect is the direct conversion of temperature differences to electric voltage and vice versa. A thermoelectric device creates voltage when there is a different temperature on each side. Conversely, when a voltage is applied to it, it creates a temperature difference. The quantity of heat generated and its sign depends on the type of contacting substances, direction and strength of the electric current

$$Q = P_{AB}It = (P_B - P_A)It$$

where Q — generation or absorption heat; I — amperage; t — time; P - Peltier coefficient, which is connected with the thermo EMF coefficient α.(P = αT, where T - absolute temperature [12]).

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Peltier element consists of one or more pairs of small semiconductor parallelepipeds - n- type and a p- type (usually bismuth telluride, Bi2Te3, and silicon germanide) which are connected in pairs by means of metal bridges. Metal bridges also serve as thermal contacts and insulated non-conductive film or ceramic plate. Pairs of parallelepipeds are connected so as to form a series connection of many pairs of semiconductors with different conductivity type so that the compounds have one sequence of (n-> p) from above, and opposite the bottom (p-> n). Electric current flows through all of the parallelepipeds. Depending on the direction of current the upper contacts cooled and the lower contacts heated - or vice versa. Thus the electric current transfers heat from one side of the Peltier element on the opposite and it creates a temperature differential between sides of Peltier element.

To determine the heat flux from the measured data of current Peltier has been calibrated based on a device shown in figure 5.

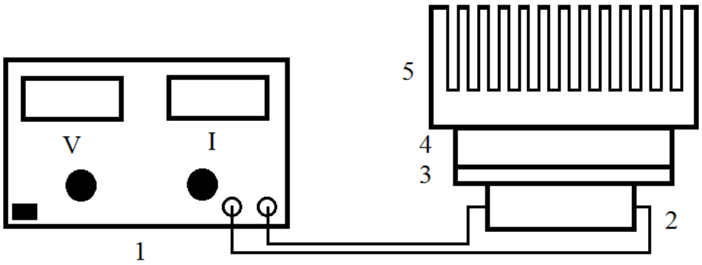

Fig 5. *The principal scheme of calibration of Peltier element (1 - generator, 2 – thermo resistor, 3 – cooper bar, 4 – Peltier element, 5 – radiator)*

The heat flux was control by varying the voltage on the thermistor. Copper plate is required for full coverage surface of the Peltier element, to prevent registration of external heat fluxes. Thermistor placed in a heat-insulating material, so all the heat flow goes through the copper plate. Peltier coefficient is P_{AB} = 0.199 J/(mA•s). Calibration graph is presented in figure 6. Assembled device allows us to measure the heat flux up to 20 mW.

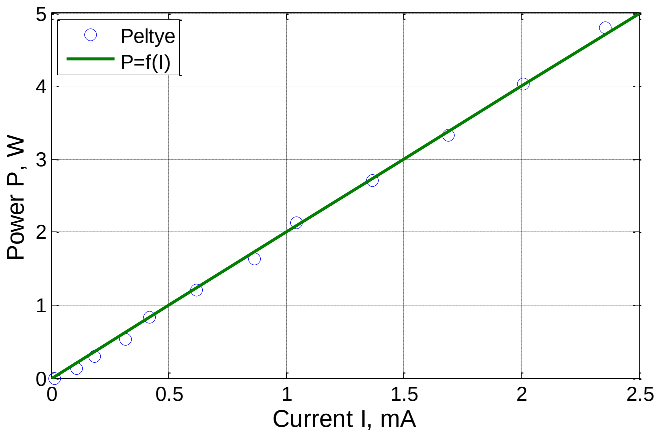

Fig 6. *Calibration graph of Peltier element*

3. Experimental results

The characteristic dependences of the rate of fatigue crack propagation at constant stress amplitude are shown in Figure 7a. Figure 7b shows the corresponding evolution of the energy dissipation rate at the crack tip. In figure 7b there are three characteristic time stages, corresponding to different modes of crack propagation. Initially the crack propagates in the intensively deformed material which has been created during crack initiation. The second regime corresponds to the Paris`s regime of crack propagation. At the third stage, the crack accelerated and we can observed a non-stationary crack propagation regime, which accompanied by intense heat dissipation.

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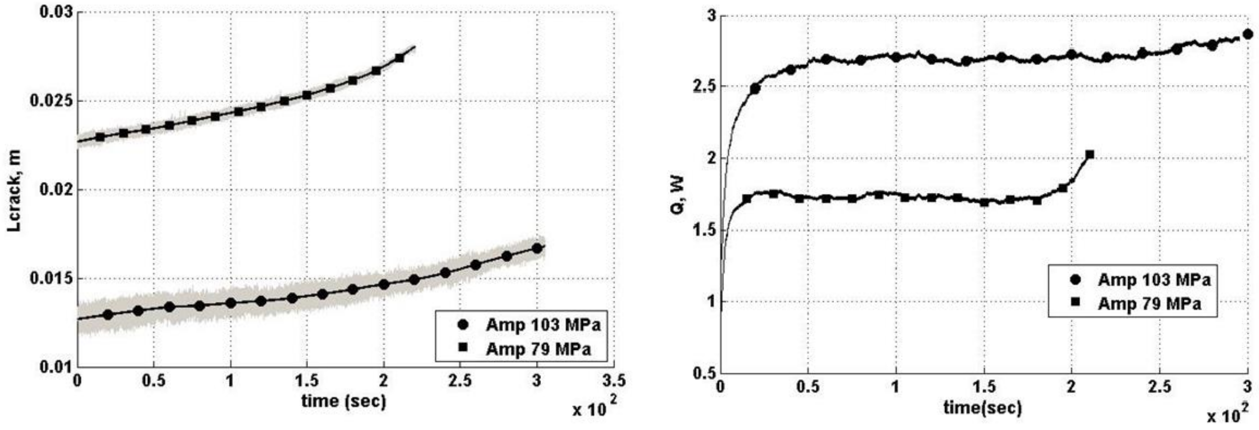

a) b)

Fig. 7. *The time dependence of fatigue cracks length in steel AISE 304 at the amplitude of the applied stress 79 MPa, and 103 MPa (a), dependence of the rate of energy dissipation at the crack tip (b).*

Figure 8 shows the results of the analysis of experimental data for three different applied stress amplitudes. The analysis of the results suggests a linear relationship between the rate of fatigue crack propagation and the multiplication of the energy dissipation rate with the current crack length.

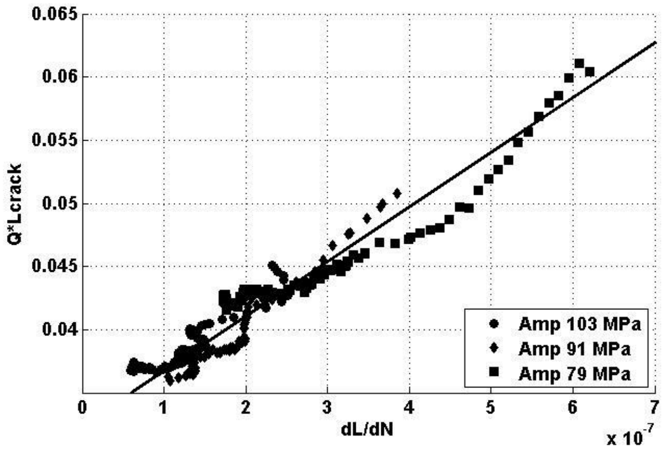

Fig 8. *Dependence the fatigue crack rate versus energy dissipation at the crack tip for different stress amplitudes (79 MPa, 91 MPa, 103 MPa).*

4. Conclusion

The study of energy dissipation at fatigue crack tip has been carried out. The analysis of the results supports the proposed hypothesis of a linear relation between the rate of fatigue crack propagation and the product of the energy dissipation rate at its tip. It gives us an opportunity to construct a kinetic equation for crack propagation in ductile materials based on the analysis of the energy balance in crack tip. This study can be considered as first attempt to understand of the physical mechanisms underlying of the process of crack propagation in ductile materials and avoid of using linear fracture mechanics framework for description of cracking of this materials. An additional detailed study is needed to obtain the thermodynamic description of the energy balance at the crack tip. As a continuation of this work we plan to combine the results of heat dissipation study with the monitoring of energy expended in the deformation process (determination of the W^p in equation (1)) and structural studies of material to clarify of the evolution value Λ - the fracture energy of the material.

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