



Experimental study of heat dissipation at the crack tip during fatigue crack propagation

A. Vshivkov, A. Iziyomova, O. Plekhov

Institute of Continuous Media Mechanics UB RAS, 614014 Perm, Russia
vshivkov.a@icmm.ru

J. Bär

University of the Federal Armed Forces, Institute for Materials Science, 85577 Neubiberg, Germany

ABSTRACT. This work is devoted to the development of an experimental method for studying the energy balance during cyclic deformation and fracture. The studies were conducted on 304 stainless steel AISE and titanium alloy OT4-0 samples. The investigation of the fatigue crack propagation was carried out on flat samples with different geometries and types of stress concentrators. The heat flux sensor was developed based on the Seebeck effect. This sensor was used for measuring the heat dissipation power in the examined samples during the fatigue tests. The measurements showed that the rate of fatigue crack growth depends on the heat flux at the crack tip.

KEYWORDS. Heat flow; Fatigue crack; Dissipated energy.

INTRODUCTION

Today, the investigation of material durability is the research trend of vital importance. Different types of structures have bottleneck areas, whose destruction can lead to irreversible consequences. Material durability is the problem of current concern due to universal use of structures and mechanisms, whose resources are not endless. The issue of timely replacement of these devices is a compromise between the prevention of catastrophic consequences and economic efficiency.

Any real engineering construction contains stress concentrators, welded joints and other potential sources of defects. The analysis of the kinetics of damage accumulation, the process of crack nucleation and kinetics of the crack development allows specialists to predict the time of structure failure and to perform in proper time a partial replacement or repair of deteriorated units of complex structures. Moreover, the repair or replacement of the worn-out parts on a timely basis is more effective than their complete replacement after mechanical damage. It is therefore very important to know the time during which the defects in the ill-behaved areas are reaching critical values.

Theoretical and experimental study of the processes accompanying the evolution of the material structure during its deformation and fracture is an actual problem of modern experimental mechanics. Its solution enables researchers to gain deeper insight into the nature of the fracture processes and to develop new, high-performance techniques for assessing

the service life of both traditional and advanced structural materials. One of the most effective approaches to the development of fracture criterion is the energy approach.

The energy balance can be calculated based on the analysis of evolution of the temperature field (for instance, measured by infrared thermography) on the sample surface, at least for flat samples. This calculation is usually associated with the need to differentiate strongly oscillating signals and to determine the parameters responsible for the interaction of the sample with environment.

One of the options for improving the reliability and accuracy of the results is the development of an independent method for measuring the power of heat sources. Such an idea was originally used for studying the energy dissipation under liquid flow [1] as well as the failure of metals [2]. In our work, this problem was solved by using a contact heat flux sensor, which was developed based on the Seebeck effect.

The results of analysis of the energy balance in the fracture zone obtained with the new heat flux sensor during the propagation of fatigue cracks in stainless steel AISE 304 and titanium alloy OT4-0 lend support to the validity of the proposed method. In this study, the thermodynamic characteristics of the process of fatigue crack propagation, such as the dissipation rate and the rate of energy accumulation at the crack tip was investigated. Also the possibility of predicting the rate of fatigue crack propagation and the time of fatigue crack transition from the stationary to nonstationary regime were considered.

THE CONTACT HEAT FLUX SENSOR

To analyze the energy balance at the crack tip a contact heat flux sensor was designed and constructed. The proposed sensor is based on the Seebeck effect, which is the reverse of the Peltier effect [3].

The Peltier effect is a thermoelectric phenomenon, in which the passage of electric current through conducting medium leads to the generation or absorption of heat at the point of contact (junction) of two dissimilar conductors. The quantity of heat and its sign depend on the type of materials in contact, the direction and the strength of the electric current:

$$Q = \Pi_{AB} \cdot I \cdot t \quad (1)$$

where Q is the quantity of dissipated or absorbed heat; I is the electric current; t is the time of current flow; Π_{AB} is the Peltier coefficient, which is related with a coefficient of thermal electromotive force.

The effect was discovered by J. Peltier in 1834 [3]. This effect is more pronounced in semiconductors, which explains their usage in the Peltier elements. A Peltier element consists of one or more pairs of small semiconductor parallelepipeds – each pair comprises one n-type and one p-type semiconductor (bismuth telluride, Bi_2Te_3 , and silicon germanide), which are connected pairwise by means of metal straps. The Seebeck effect [3] lies in the fact that thermo-electromotive force occurs in a closed circuit consisting of dissimilar conductors provided that the contact zones are kept at different temperatures. A circuit including only two different conductors is called a thermocouple.

The quantity of heat absorbed or dissipated by the element is directly proportional to the current intensity and the time of its passage. Fig. 1 presents a schematic diagram of the heat flux sensor. The following notation is used in Fig. 1: sample (1), the heat flux sensor (2). A thermal contact between the sample and the sensor is provided due to the introduction of the thermal paste. Structurally, the sensor comprises two Peltier elements ("measuring" (2) and "cooling" (3)), thermocouples (5), (6) and the radiator (4). The measuring Peltier element is connected to a low-resistance resistor of $1.2 \square$ (7). To measure the heat flow through the "measuring" Peltier element during the experiment the temperature on its free surface keeps constant. The cooling peltier element caulked with a radiator was connected with the "measuring" Peltier element. This cooling system has feedback and is controlled based on two temperature sensors located between "measuring" and cooling Peltier elements and far from the studied sample in the zone with constant temperature.

The signal from the sensor (voltage at the resistor (7)) is measured by the amplifier and registered in the ADC of the microcontroller. The data are transmitted from the microcontroller to the personal computer for further processing. The "cooling" Peltier element is controlled via pulse width modulation.

These sensors were calibrated using a device with a controlled heat flux. The calibration scheme is shown in Fig. 2. A wire resistor with the known resistance is glued on a plastic plate with a size equal to that of test samples. The heat isolating system provides the heat flux from the resistance to the sensor only. The heat flow was calculated using the values of the resistor voltage and the electric current across the resistor.

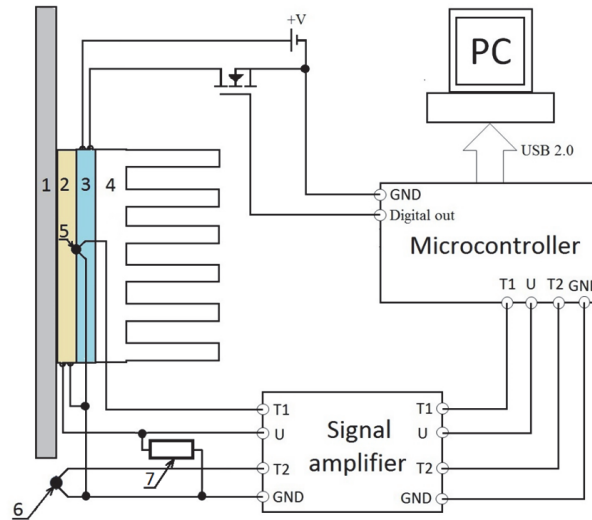


Figure 1: Schematic of the device. 1 – testing sample; 2 – “measuring” Peltier element; 3 – “cooling” Peltier element; 4 – radiator; 5, 6 – thermocouple; 7 – resistor.

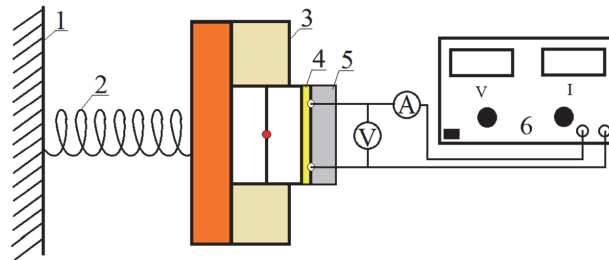


Figure 2: Sensor calibration scheme (1 – back side of testing machine, 2 – spring, 3 – sensor, 4 - resistor 5 - plastic sample 6 - DC power supply source).

The sensor is calibrated directly in the testing machine, in conditions closely approximating the experimental conditions. A calibration curve for each sensor was obtained based on the experimental data (Fig. 3). The sensor signal is correlated to the heat flux dissipated by the resistor. The graphs presented in Fig. 3 show a linear dependence that agrees well with the theoretical prediction.

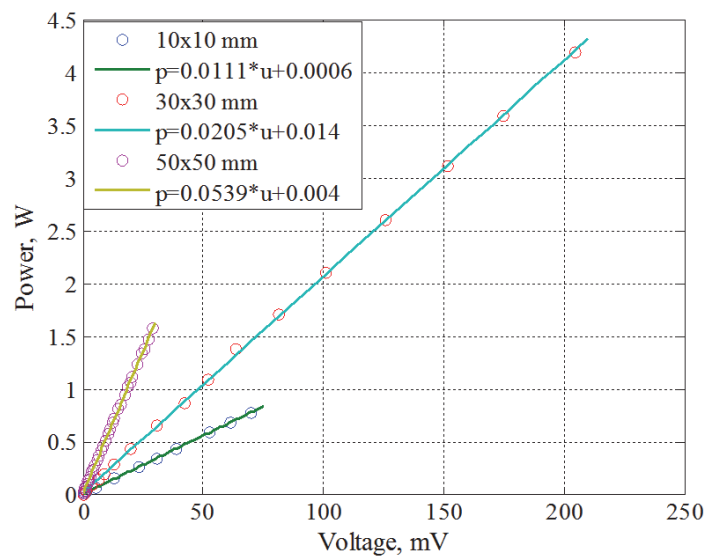


Figure 3: Calibration graph of heat flow sensors.



EXPERIMENTAL SETUP

A series of samples made from stainless steel AISE 304 and titanium alloy OT4-0 were tested in the developed device. The tests were carried out for samples of different sizes and with different types of stress concentrators. The geometry of the samples is shown in Fig. 4. During tests the samples were subjected to cyclic loading of 10 Hz with a constant amplitude and stress ratio $R = -0.1$. The crack length in the course of the experiment was measured by the potential drop method [4].

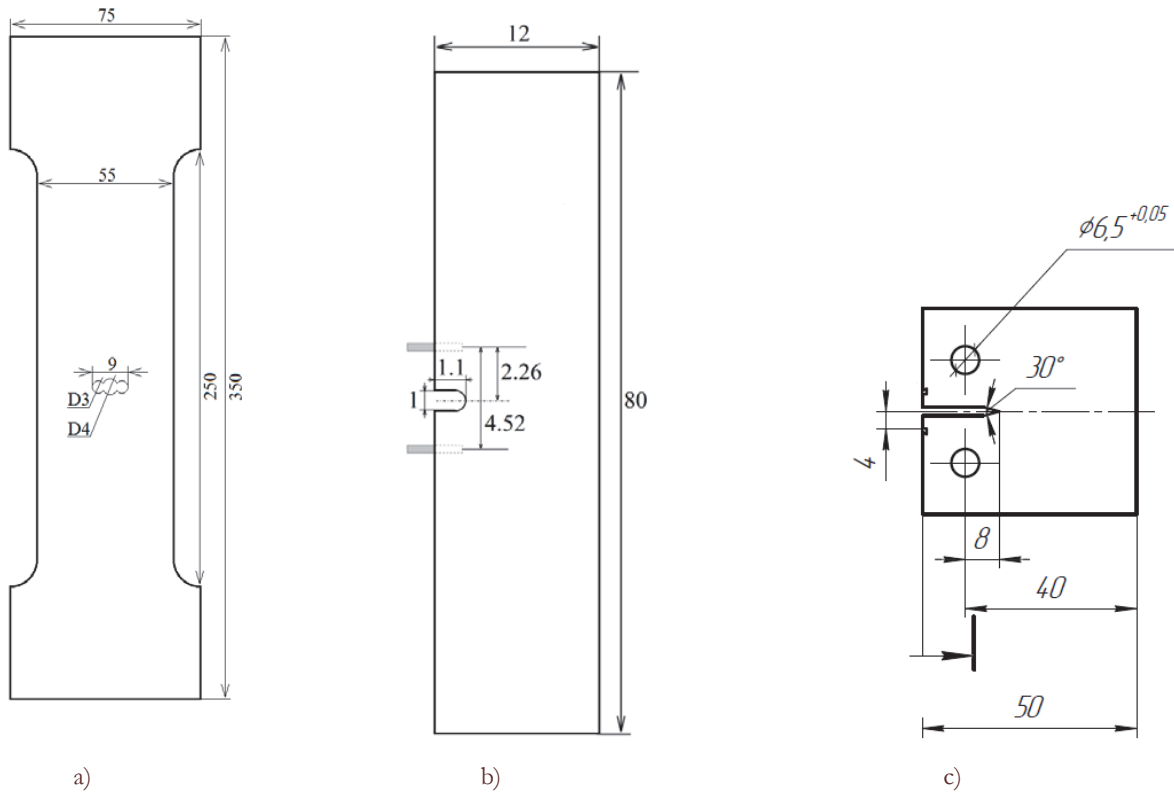


Figure 4: Geometry of samples: a, b – steel, c – titanium.

Contact heat flux sensors were made for each type of the sample. The sizes of sensor are shown in Fig. 5.

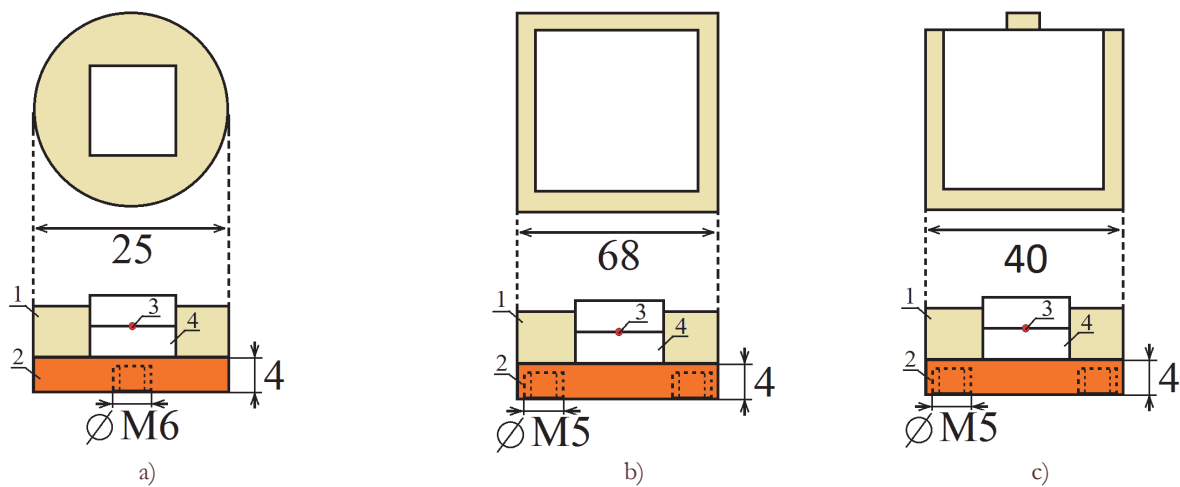


Figure 5: Sizes of sensors: a) – Peltier element 10x10 mm., b) – Peltier element 50x50 mm., c) – Peltier element 30x30 mm. (1 – plastic, 2 – copper plate, 3 – thermocouple, 4 – Peltier elements).

THE STUDY OF THE THERMOELASTIC EFFECT

The sensitivity of the sensors was illustrated by the study of thermoelastic effects in metals under investigation. The amplitude of applied stress did not exceed 40% of the limit of proportionality, which provided the absence of sample heating caused by plastic deformation.

In the goal of the experiments was the investigation of the accuracy of the proposed method and the influence of the conditions of heat exchange with the environment. The experimental data was compared with the analytical solution of the Kelvin equation. Additionally, the influence of the conditions of contact between the sensor and the sample on the measured parameters was checked. The amplitude of the stress was 5 kN, the frequency of 1 Hz, the stress ratio $R = -1$. The experimental results for various conditions of sensor contact with the sample are shown in Fig. 6.

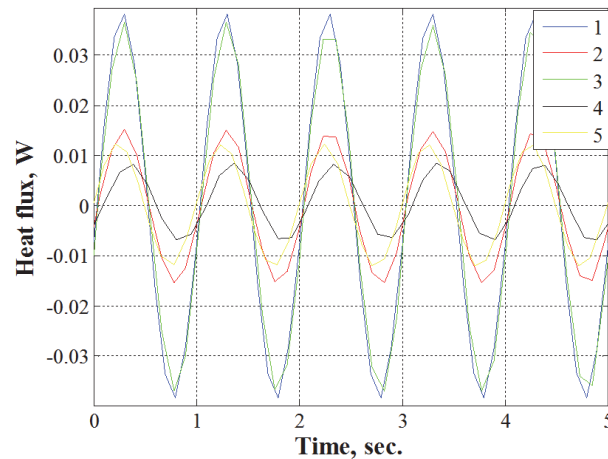


Figure 6: Power of heat flux during the thermoelastic test (1 – the analytical solution of the Kelvin equation; 2 – the experimental data from the sensor pressed by the spring to the sample; 3 – the experimental data from the sensor corrected by the consideration of whole free surface of the sample; 4 – the experimental data from the sensor located with a gap of 0.5 mm. from the sample; 5 – the experimental data from the sensor located with a gap of 0.1 mm. from the sample.)

Fig. 6 shows three variants of mounting the sensor to the sample: a tripod with a gap of 0.5 mm (4) and 0.1 (5), and the pressing of sensor to the sample by the spring (3). Analysis of the results presented in Fig. 6, allows us to conclude that there is no influence of friction on the measured heat flow. The measured value with a tripod is substantially less than the theoretically calculated (graphs (4) and (5) in Fig. 6). In this case, it is assumed that the sensor does not change the conditions of heat exchange of the sample and the environment (heat dissipation is the same in all directions). To correct the heat measured data from the pressed sensor (2) we assumed that the sensor with cooling system does not change the heat transfer conditions and multiply the data by a factor taking into account the whole free surface of the sample. Taking these hypothesis into account we can obtain a complete coincidence of measured and theoretical values (graphs (1) and (3) in Fig. 6).

THE STUDY OF FATIGUE CRACK PROPAGATION

The developed sensor was used to study the heat dissipation caused by growth of fatigue cracks. Typical result of measurements of the heat flux during the experiment is presented in Fig. 7. The plots can be divided into three parts. Short initial increasing part corresponds to starting of crack propagation (part 1). The second part with constant heat flux corresponds to the regime of short crack propagation (part 2). The last part of the plot (part 3) is characterized by sharp increasing of heat dissipation. During this part we observe the long crack propagation process. The last part is finished by specimen failure.

Fig. 8 presents the experimental data to illustrate general regularities in the dynamics of fatigue crack growth. The tests presented in the figure were carried out on the samples made from steel. The geometry of the samples is presented in Fig. 4a. The stress amplitude was constant during the test. The unfilled point corresponds to the results of the heat measurement with the developed sensors. There are three different stress amplitudes in Fig. 8 with corresponds to following applied forces: 13 kN (unfilled squares), 15 kN (unfilled circles) and 17 kN (unfilled diamonds). The filled marks



corresponds the heat flux calculated by treatment of surface temperature evolution measured by independent way. Based on the data presented in Fig. 8 we can conclude that there is a linear relation between crack rate and product of crack length and heat power from the crack tip. This conclusion was confirmed by the results obtained with the other sample geometries presented in Fig. 4. All tests were carried out with constant stress amplitude.

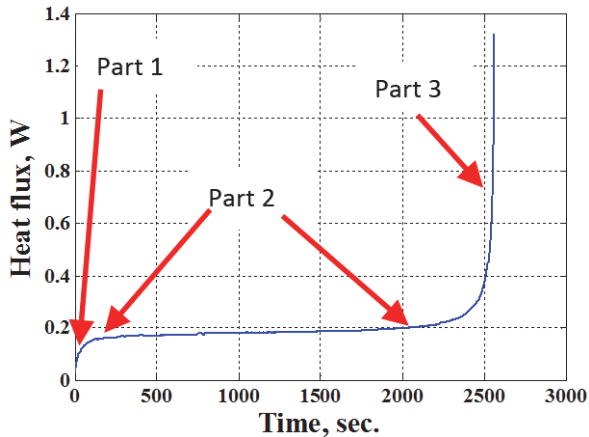


Figure 7: The characteristic dependence of the power of heat flux from the crack tip.

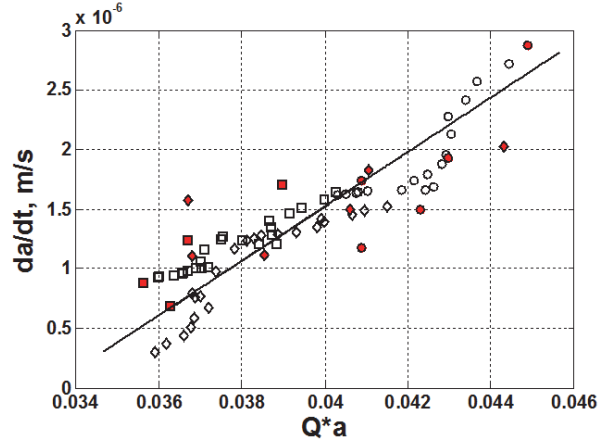


Figure 8: The relation between fatigue crack rate and the fatigue crack length multiplied by the power of heat flow.

CONCLUSION

The paper describes the structure and performance of the heat flux sensor which was designed based on the Seebeck effect. This sensor can be used to analyze the energy balance of the material during the deformation process either in combination with the method of infrared thermography (for its verification), or independently. In the case of its independent usage the loss of information about the spatial distribution of the heat is compensated by the possibility of long-term measurements. With this technique a comprehensive investigation into the processes of energy dissipation during the propagation of fatigue cracks in metal alloys was done. The analysis of the results allowed putting forward the hypothesis for a linear relationship between the rate of fatigue crack propagation and the product of the rate of energy dissipation by the length of the crack. The developed method can be used to calculate the value of the dissipated energy at any moment of the material lifetime. One of possible promising continuation of the work is a combination of this result with the calculation of applied energy. It could give us an opportunity to estimate a stored energy (cold work) of deformation. The stored energy is widely used to formulate a criterion of material failure [5, 6]. Thus, the proposed method can be applied to assess the state of the material.

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