The study of the dissipation heat flow and the acoustic emission during the fatigue crack propagation in the metal

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Abstract. This work is aimed at developing a thermodynamic approach to describing the propagation of fatigue cracks in metals. An attempt is made to explain the change in the character of heat dissipation at different stages of crack propagation: the nucleation, the Paris regime, the critical growth. The studies were conducted on two metal alloys: 304 AISE stainless steel and titanium alloy VT 1-0. The investigation of the fatigue crack propagation was carried out on flat samples with stress concentrators. The stress concentrator was the triangular side notch. To monitor the dissipated thermal energy it was used method of infrared thermography and the contact heat flux sensor based on the Seebeck effect. Also the registration system of the acoustic emission was used for more exactly description of the fatigue crack propagation. Analysis of acoustic emission data on the basis of cluster analysis made it possible to classify various mechanisms of the damage process. A correlation was found between the integral dissipated thermal energy and the total energy of acoustic emission during the propagation of a fatigue crack. The joint application of these techniques has made it possible to reveal the moment’s activation of failure mechanisms and their relationship to the dissipated heat flux.

1. Introduction

Theoretical and experimental study of the processes accompanying the evolution of the structure of the material during its deformation and fracture is an actual task of modern experimental mechanics. Its solution allows for a deeper understanding of the nature of the destruction processes and the development of new effective methods for assessing the operational resource of construction materials. One of the actual problems in this area is the problem of predicting the rate of propagation of fatigue cracks in metals. Many authors proposed dependencies linking the rate of crack growth and such quantities as the J-integral, the work of plastic deformation, the size of the zone of plastic deformation, the amount of dissipated energy and other [1-4].

It is now well known that the change in the shape of metallic samples during plastic deformation is accompanied by the formation and movement of defects in the structure of the material that cause the energy conversion processes. The classical assumption of an almost complete dissipation of the energy of deformation into heat [5] turns out to be correct only in a limited number of cases. Today, there are
techniques that allow real-time monitoring on the temperature change of the sample during the deformation process (the method of infrared thermography) and the number and nature of the defects formed (acoustic emission method). These data allow us to estimate the number of emerging defects and the rate of energy dissipation in the material during the process of damage.

The power of the heat flux 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 [6-8]. 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 [9] as well as the failure of metals [10]. This problem was solved by using a contact heat flux sensor, which was developed based on the Seebeck effect.

This work is devoted to the study of the features of energy dissipation and acoustic emission in stainless steel AISE 304 and titanium alloy OT4-0 during the fatigue crack propagation. The main task of this study is to establish the relationship between the processes of heat dissipation and the evolution of the structure of the material directly during the loading process. At carrying out of experimental investigation simultaneously three methods of nondestructive control were used and their results were compared. In the course of the experiment, the processes accompanying the evolution of the structure of the material were controlled by the infrared scanning, the measurement of the heat flux by the contact sensor and by the acoustic emission method.

2. Experimental setup
A series of samples made from stainless steel AISE 304 and titanium alloy VT1-0 were tested in the servo-hydraulic testing machine Instron 8802. The tests for samples with stress concentrators were carried out in the Center of Experimental Mechanics. The geometry of the samples is shown in Figure 1. During tests the samples were subjected to cyclic loading of 20 Hz with constant stress amplitude and ratio R = 0. The crack length in the course of the experiment was measured by the potential drop method [11, 12]. The electrical potential drop method is accepted as being capable of monitoring the fatigue crack and propagation in steel structures. The size of a crack in a steel member is predicted by applying a constant d.c. (direct current) or a.c. (alternating current) to the member and by measuring an increase in electrical resistance due to the crack. In this case, the potential method is capable of a sensitivity as fine as 0.02 mm for a d.c. 5 A.

![Figure 1. Geometry of samples.](image)

To analyze the dissipated energy 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.

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.

The quantity of heat absorbed or dissipated by the element is directly proportional to the current intensity and the time of its passage.

\[ P = \Pi_{AB} I \]

\( P \) – the power of heat flux; \( I \) – the direct current; \( \Pi_{AB} \) – Peltier coefficient.

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

Figure 1 presents a schematic diagram of the heat flux sensor. The following notation is used in figure 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 Ohm (7). To measure the heat flow through the "measuring" Peltier element during the experiment the temperature on its free surface should be a 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. 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.

The evolution of the temperature field 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.

The system Amsy-5 Vallen was used for registration of the acoustic emission signal. This system had two broadband M31 sensors with a working range of 300-800 kHz. For amplification, AEP4 preamps (gain 34 dB) were used. The acoustic emission transducers were attached to the surface of the sample with a cyanocrylate adhesive. Continuous acoustic emission was recorded with frequency of
2 MHz. Parameters of acoustic emission (maximum amplitude, energy) were stored every 40 milliseconds (a waveform record also was made after 40 milliseconds with a duration of 4 ms). The location of acoustic emission sensors is shown in figure 3.

The principal scheme of experiments is presented in figure 4, 5.

Figure 3. The location of acoustic emission sensors.

Figure 4. Schematic of the measured equipment.

Figure 5. The sample with the measured equipment.

The following notation are accepted in figure 3: 1 – specimen under testing, 2 – grips of testing machine, 3 – the contact heat flux sensor, 4 – the potential drop measuring setup to monitor the crack length, 5 – the infrared camera, 6 – sensors of acoustic emission.

3. Results
A series of samples from the titanium alloy VT1-0 and stainless steel AISE 304 was tested as outlined above. The propagation of the fatigue crack corresponded to the Paris law (figures 6).
3.1. The dissipated thermal energy

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 figure 7.

\[
Q_{\text{int}}(x, y, t) = \rho c \left( \frac{\partial \theta(x, y, t)}{\partial t} + \frac{\theta(x, y, t) - T_0}{\tau} \right) - k \left( \frac{\partial^2 \theta(x, y, t)}{\partial x^2} + \frac{\partial^2 \theta(x, y, t)}{\partial y^2} \right)
\]  

where \( \tau \) is time constant which is related to the heat losses[13,14]. The coefficient \( \tau \) was measured before each test.
The processing of infrared data was made by algorithm of movie compensation and filtering. These algorithms were described in details in [15].

3.2. The acoustic emission
Figure 8 shows the dependence of the energy of the acoustic emission for two channels and the crack length on time. There is a significant and non-monotonic change in the energy of the acoustic emission during the cyclic deformation of the sample (more than 2-time). The sharp growth of the crack at the end of the test is accompanied by a sharp increase in the energy of the acoustic emission.

![Figure 8](image)

**Figure 8.** The signal of the acoustic emission and the crack length during the experiment.

For a more detailed analysis of the stage of the acoustic emission variation, the dependences of the first two statistical moments for the accumulated energy of the acoustic emission on time were constructed (figure 9, 10). Analysis of the obtained results showed that the moment of occurrence of the crack \( t_{2,2} \), fixed by the potential drop method, corresponds to a break on the dependences of the first two statistical moments recorded by the more remote sensor (channel 6). At the same time, the same break is observed on the acoustic emission signal from channel 5, but for an earlier time \( t_{2,1} \). The observed difference can be caused by closer positioning of the AE sensor to the crack tip (channel 5), which provides its greater sensitivity in comparison with channel 6. It should also be noted that for data from a closer-lying acoustic sensor, there is a difference in estimates of the moment of appearance of a crack \( t_{2,1} \) and \( t'_{2,1} \) for first and second statistical moments. This means that the more "sensitive parameter" is the second statistical moment, which begins to change in the first place.

![Figure 9](image)

**Figure 9.** The dependences between the mean energy of the acoustic emission on the time, combined with the time dependence of the crack length.
On the obtained dependences one can also single out another characteristic time $t_1$ ($t'_1$), which, apparently, characterizes the moment of appearance of the local zone of plastic deformation, in which the fatigue crack will appear in the future. This time moment is also differently identified on the time dependences of the statistical moments. Here it is important to note two features:

1. if the time instant $t_1$ is identified on the dependence of the average accumulated energy only for the more remote acoustic sensor, then the dependence of the standard deviation is for both, and for both is the same;

2. The mean level of accumulated energy of the acoustic emission registrated on the closer acoustic sensor only at the initial stage of deformation exceeds the energy level of the sensor from the more remote sensor. This is due to the fact that after the starting the crack propagation, a closer sensor is placing behind the crack tip.

A comparison of the acoustic emission and the heat flux during the propagation of the fatigue crack is also performed. For comparison of the methods, the integral energy is normalized to the maximum value. From the results presented in Figure 11, it can assume a qualitative agreement of the integral thermal energy and cumulative energy of the acoustic emission.

**Figure 10.** The dependences between the standard deviation of the accumulated energy on the time, combined with the time dependence of the crack length.

**Figure 11.** The comparison of the integral dissipated thermal energy and the cumulative energy of the acoustic emission.
4. 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 dissipated energy of the material during the deformation process either in combination with the method of infrared thermography (for its verification), or independently. With this technique a comprehensive investigation into the processes of energy dissipation during the propagation of fatigue cracks in metal alloys was done.

As a result of the analysis of the acoustic emission signal, it is shown that the use of the method in a cyclic testing of the metal makes it possible to identify the moment of appearance of the crack. The method has a greater sensitivity compared to the method of the potential drop method or the method based on the power of the dissipated energy. Also, the method of acoustic emission makes it possible to identify the moment of the beginning of preparation of the material (the appearance of local zones of plastic deformation) to the appearance of a fatigue crack. When comparing methods (acoustic emission and energy approach), correlations between integral dissipated thermal energy and the cumulative energy of acoustic emission are revealed.

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