The study of energy dissipation at crack tip using infrared thermography coupled with contact heat source sensor.

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Abstract. The work is devoted to a development of technique for estimation of energy balance at crack tip and, as a consequence, to find a physical based relation for calculation of fatigue crack rate. Nowadays, the most popular way to study the temperature evolution in metals under deformation and failure is infrared thermography (IRT). But this technique requests some assumptions about heat losses process and post processing algorithms to get the value of heat dissipation. The goal of this work is to develop the technique which allows avoiding the additional assumptions and give two different ways for energy dissipation measurement. A proposed technique is a combination of contact (heat flux sensor) and noncontact (IR camera) equipment which could be used during mechanical test. The efficiency of technique is illustrated by study of crack rate – energy dissipation law for fatigue cracks in steel and titanium alloys (AISI304, Ti-0.8Al-0.8Mn).

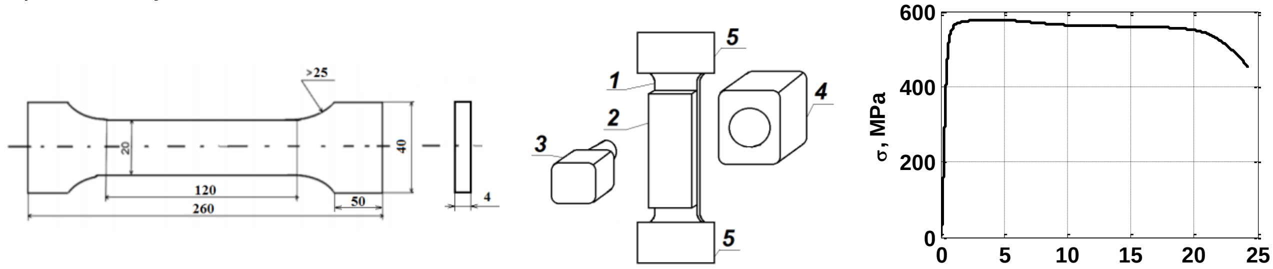
Introduction

IRT is widely used in different areas of life such as defectoscopy, warfare, security control etc. Also IRT has an important application in scientific researches as a relatively simple noncontact method of temperature measurement. There are a lot of works devoted to study of material state under deformation on the basis of so-called energy approach, where IRT is used to determine the mechanical [1, 2] and thermal characteristics [3-5] and to evaluate the damage degree of material by construction of heat source field of material surface. For this purpose the determination of time constant of heat losses is necessary. Usually the additional cooling test is performed to define this constant.

In present work the heat flux sensor is proposed to avoid additional experiment and to find the required time constant during mechanical test directly. The efficiency of technique is illustrated by study of crack rate – energy dissipation law for fatigue cracks in steel and titanium alloys. As a result, the correlation between heat flow caused by plastic deformation near the crack tip and crack propagation rate was found.

Materials and experimental conditions

In this work titanium alloy specimens were tested under quasistatic tensile conditions. Smooth dog-bone-shaped specimens were used (figure 1-A). Figure 1-B shows the scheme of the experimental setup consisting of electric mechanical testing machine Shimadzu AG-X Plus (300 kN), IR camera FLIR SC5000, heat flux sensor and video extensometer Shimadzu TRViewX240S. Figure 1-C illustrates a stress-strain curve obtained experimentally. The strain rate was $15 \cdot 10^{-4}$ sec-1.



A *b* *c*

Fig.1. A – Geometry of specimen for tensile testing; B - scheme of experimental setup (1 – specimen, 2 – heat flux sensor, 3 – video extensometer, 4 – infrared camera, 5 – grips of the testing machine); C – experimental stress-strain curve for titanium alloy Ti-0.8Al-0.8Mn

The developed heat flux sensor is described in details in [6]. This sensor allows us measuring the heat flux on the specimen surface during mechanical test in combination with IR camera. As a result of experiment the stress-strain curve of titanium alloy Ti-0.8Al-0.8Mn, evolution of temperature field of specimen surface and heat flux were obtained by video extensometer, IR camera and heat flux sensor respectively.

Determination of time constant by heat flux sensor and by cooling test

On the basis of temperature field obtained by IR camera, the heat flux was calculated according to the heat conductivity equation (1) integrated on volume.

$$s(x,y,t) = \rho c\left(\frac{\partial T(x,y,t)}{\partial t} + \frac{T(x,y,t) - T0(x,y)}{\tau}\right) - k\left(\frac{\partial^2 T(x,y,t)}{\partial x^2} + \frac{\partial^2 T(x,y,t)}{\partial y^2}\right) \quad (1)$$

where T(x,y,t) – temperature field of specimen surface, T0(x,y) – initial temperature field of specimen surface, ρ – density (4475 kg/m3), c – heat capacity (456 J/(kg·K)), k – heat conductivity (6.6 W/(m·K)), s – unknown specific power of the heat source (W/m3), τ – the constant related to the losses by heat exchange of specimen and environment.

In this work the time constant τ was evaluated by two ways. The first one was the standard method of cooling test after local point heating of specimen surface. In this case, the heat conductivity equation (1) with zero heat source value (s(x,y,t)=0) was used. The second way was using the data of heat flux sensor. The time constant τ was picked out so as to provide a good correlation between heat sources values obtained by contact sensor and on the basis of IRT data. According this data, the value of time constant τ is 20.45 s. The heat flux versus time obtained by contact sensor and on the basis of infrared thermography data with τ=25 s.

Fatigue crack propagation

The proposed technique allows us to study the effect of heat dissipation at crack tip on crack rate. Heat dissipation process associated with crack growth could be divided into two parts. The first one corresponds to the constant value of heat flux and small changes of crack length. The second one is characterized of avalanche growth of heat flux and significant changes in crack length. To compare two stages, experimental data were normalized as it is shown in equation (2).

$$Q_1 a_1' = \frac{Q_1 a_1 - Q_1 a_1^{min}}{Q_1 a_1^{max} - Q_1 a_1^{min}} \quad Q_2 = \frac{Q_2 - Q_2^{min}}{Q_2^{max} - Q_2^{min}} \quad \Delta K_i' = \frac{\Delta K_i - \Delta K_i^{min}}{\Delta K_i^{max} - \Delta K_i^{min}} \quad (2)$$

Figure 2a and 2b illustrates corresponding values of Q_1 and ΔK_1 (Stage 1), Q_2 and ΔK_2 (Stage 2). Figure 2c illustrates linear dependence between crack growth rate and normalized values from expression (2).

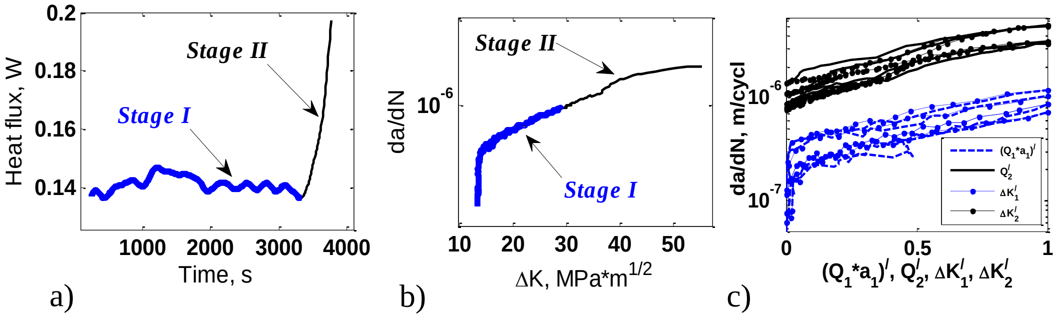


Fig.2. Experimental data: a) heat flux during fatigue test; b) crack growth rate versus range of stress intensity factor c) crack growth rate versus normalized values from expression (2).

Conclusions

The proposed technique allows us to measure the energy dissipation under mechanical test. The application of this technique shows two stages energy dissipation under fatigue crack propagation in metals. In the first one the linear dependence between crack growth rate and heat flux multiplied crack length was shown. In the second stage the linear dependence between crack growth rate and heat flux was obtained. The physical reason for these results could be the different mechanisms (different value of specific stored energy) determining the crack propagation at different stress concentrator range value relations. The results could allow one to use the value of the heat flux in crack tip area as an alternative way to estimate the crack growth rate independent on loading conditions.

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