Approximation of Heat Dissipation - Crack Rate Curve for Fatigue Crack in Stainless Steel

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Abstract. The experimental and theoretical analysis of thermodynamical peculiarities of heat flux at the fatigue crack tip during its propagation was made in presented work. The goal is to elucidate the relation between heat flow at the crack tip and kinetic of fatigue crack propagation for different loading conditions. The plane specimens with notch made from stainless steel (AISI 304) were studied. There were two types of specimens for uniaxial loading and one type for biaxial loading. A heat dissipation during fatigue crack propagation was measured by simultaneous use of contact and noncontact techniques. The samples were subject to cyclic loading with constant stress amplitude and different biaxial coefficients. The functional dependence between crack propagation and heat flow at the crack tip was received by experiment measurement and analytical calculation. This relation depends on only type of material and righty for all fracture mode.

1. Introduction

A number of approaches has been developed to study the processes of nucleation and propagation of fatigue cracks in metals [1–4]. Structural changes caused by plastic deformation of the material occur at different scale levels. They are accompanied by the accumulation and dissipation of energy. The evolution of these processes integrally reflects the degree of material damage and allows one to estimate the material state at various stages of fatigue crack evolution. The development of a universal approach based on a joint analysis of the kinetics and thermodynamics of damage accumulation, crack initiation and crack propagation will allow one not only to predict the time when defect reaches a critical size, but also to timely perform partial replacement or repair of weak points in the structure.

The actual engineering structures operate under complex types of loading. So, it is of considerable interest to study the behavior of materials under mixed loading conditions that combine mode 1 and mode 2 fractures. In sufficiently plastic structural materials the crack evolution begins when the plastic deformation near its tip becomes large (of the order of 10 percent). This irreversible process is accompanied by the release and accumulation of energy, which leads to a local temperature change in the crack tip area and the occurrence of a heat flux.

Nowadays, non-destructive testing methods are widely used by various scientific groups such as [5,6,7] to assess the condition of materials and structures. Traditionally the Paris low is applied to predict the fatigue crack propagation. This low is synthesis of experimental data and correctly works with small plastic deformation. So it will be better to use another parameters to describe the fatigue crack propagation. Many authors use the thermodynamics approach, which are based on the hypothesis that, the evolution of fatigue crack determined by energy balance in the crack tip.

We used approach proposed in [8] to calculate plastic strain work as total energy dissipated in reversible (cyclic) and monotonic plastic zones independently. The plastic strain energy at the crack tip was determined by analytic technique. This approach assumes a hypothesis that there is a relation between elasto-plastic and elastic strain fields near a crack tip in terms of Young’s and secant plasticity modules [9]. It was first proposed as an empirical expression for the central crack in a wide sheet under tensile loading in normal direction to the crack trajectory.
It was shown that energy which dissipated in cyclic plastic zone does not depend on the crack growth rate. This dissipation is fully determined by the spatial size of a cyclic plastic zone and the characteristic diameter of the yield surface. For isotropic hardening materials, the characteristic size of the yield surface and, as consequence, to energy dissipation at a constant crack growth rate is a function of applied stress amplitude. Dissipation properties of material in the monotonic plastic zone depends on characteristic diameter of the yield surface and crack growth rate. The relation between crack propagation rate and heat dissipation rate on the base of this statement is presented in [10, 11]. The comparison between the experimental data and theoretical calculation of heat dissipation during fatigue crack propagation under uniaxial and biaxial loading was made to verify the proposed approximation. The comparison shows good qualitative agreement between the phenomenological predictions and the obtained experimental results.

2. Experimental setup
Uniaxial and biaxial fatigue tests were made to determine the peculiarities of heat dissipation at fatigue crack tip in stainless steel AISI 304. Figure 1 illustrates geometry of specimens with notch. The chemical composition of stainless steel AISI 304 described in table 1.

![Figure 1. Geometry of samples for uniaxial loading type 1 (a) and type 2 (b), for biaxial loading (c)](image)

| Table 1. The chemical composition of stainless steel AISI 304. |
|------------------|---|---|---|---|---|---|---|---|
| Fe | C | Si | Mn | Ni | S | P | Cr | Cu | Ti |
| ~69 | 0.08 | 0.8 | 2 | 9-11 | 0.02 | 0.035 | 17-19 | 0.3 | 0.7 |

Uniaxial test was carried out on two types of specimens with different levels of applied stresses with frequency of 10 Hz and a stress ratio R = 0.1 for first type (figure 1a) and R = -1 for second type (figure 1b). The electric method [12] was used to determine the crack length in uniaxial test.

The biaxial test had the load frequency of 5 Hz, stress ratio R = 0.1 and different biaxial coefficient η=Px/Py (1, 0.5, 0). The optic technique was used for determined a crack length.

The experimental part of work was carried out in three different scientific platforms. There are Kazan Scientific Center of the Russian Academy of Sciences (biaxial fatigue tests), center of experimental mechanics in Perm National Research Polytechnic University and Munich University of the Federal Armed Forces (uniaxial tests).
The heat dissipation during fatigue crack propagation was measured by both using of infrared thermography method and contact measurement. The contact measurement allow us to verify the infrared data and record the heat dissipation continuously during the tests. Description of contact measurement of heat dissipation is presented in [13].

3. Results
The figure 2 shows the kinetic diagram for fatigue damage (according Paris’ law) with crack growth rate about $10^{-7} - 10^{-4}$ m/cycle. Value of stress intensity factor was determined by crack length, geometry of samples and loading conditions [14]. However, the character of energy dissipation during the crack propagation process can be divided into two parts. The first one is characterized by a constant value of heat flux. The second one demonstrates a sharp increasing in heat flux at the end of experiments (figure 3). Black circle shows the dividing point of these stages which didn’t seem on kinetic diagrams of fatigue damage.

![Figure 2](image)

**Figure 2.** Kinetic diagram for fatigue damage: type 1 $R = 0.1$ (a), type 2 $R = -1$ (b) and biaxial $R = 0.1$ (c) loading.

![Figure 3](image)

**Figure 3.** Heat dissipation during uniaxial type 1 $R = 0.1$ (a), type 2 $R = -1$ (b) and biaxial $R = 0.1$ (c) fatigue tests, $\eta$ is the biaxial coefficient.

In previous work [15] analytical assumption between crack growth rate and heat dissipation was proposed. The energy of plastic deformation work can be described as:

$$U_p = W_1(\sigma, r_p) + W_2(\sigma, r_p) \frac{dl}{dN} = \alpha \sigma^2 + \beta \sigma^2 \frac{dl}{dN}$$  \hspace{1cm} (1)

The experimental data allow us to calculate a constants in equation (1) ($\alpha = 5.66e-18$ [W/Pa2]; $\beta = 4.34e-11$ [W/(Pa2*m)]). Constant $\alpha$ corresponds constant value of heat dissipation curve in the start of fatigue test (figure 4a). Constant $\beta$ is determined by relation between heat dissipation and crack growth rate (figure 4b).
Figure 4. Heat dissipation curve for determine of constant $\alpha$ (a) and typical curve for determine constant $\beta$ (b).

This let us to suggest relation between heat dissipation and crack growth rate for different loading loadings. Theoretical analysis and measured value of heat dissipation during fatigue tests are presented in figures 5, 6, 7. Theoretical calculation was made by equation (1) and experimental data about evolution of crack length.

Figure 5. Heat dissipation curve at fatigue crack tip for samples type 1.

Figure 6. Heat dissipation curve at fatigue crack tip for samples type 2.
As a result, we have linear relation between crack growth rate and heat dissipation (figure 8a) Also there is universal relation between normalized heat dissipation by equation (2) and crack growth rate (figure 8b). The character of this relation is same for different loading conditions.

In figure 8b, there is normalization for heat dissipation by equation (2):

$$Q^* = \frac{Q}{\sigma^2} - \alpha \frac{dl}{dN}$$

(2)

4. Conclusion

The uniaxial and biaxial fatigue tests were made to verify the theoretical approach to describe the heat dissipation during fatigue crack propagation in stainless steel AISI 304. It was experimentally confirmed that energy of plastic deformation can be independently calculated for monotonic and cyclic zones.

The resulting ratio for heat dissipation and crack growth rate confirms assumption about stages of crack propagation. Based on the equation (1) we can conclude that for small crack rate (first stage) the plastic strain energy and, as a consequence, heat flux at crack tip is proportional to the applied stress amplitude. In second stage energy dissipation determined by applied stress amplitude and crack growth rate.

Experimental data allow us to determine a universal coefficients of this approximation for all studied loading conditions: $\alpha = 5.66\times10^{-18}$ [W/Pa2]; $\beta = 4.34\times10^{-11}$ [W/(Pa2*m)]. Universality of this correlation
gives promising possibilities in development of new techniques for estimation of fatigue behavior of metallic structures under complex loading.

Acknowledgements
The results about uniaxial fatigue tests were obtained within the framework of state task; state registration number of the topic AAAA-A19-119013090021-5. The reported study about biaxial fatigue tests was funded by RFBR, project number 20-31-70018.

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