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Abstract

The investigation of the fatigue crack propagation was carried out on flat samples with stress concentrator made from stainless steel AISE 304. The earlier developed contact heat flux sensor based on the Seebeck effect was used to monitor the heat flux from the crack. It gives us an opportunity to correlate the heat dissipation and crack propagation rate under constant stress amplitude. The experiments with the constant stress intensity factor have shown a decrease of the energy dissipation under constant crack rate. To explain this result the presented theoretical analysis of the stress field at the fatigue crack tip was carried out. It allows us to describe the energy flux from the crack tip as sum of two functions describing the energy dissipation in monotonic and reversible plastic zones separately. It has been shown that dissipation in reversible plastic zone is a function of the applied stress amplitude only. This fact leads to the decrease of the heat dissipation under constant stress intensity factor due to the decrease of the applied stress amplitude.

Theoretical and Experimental Analysis of the Energy Dissipation at Fatigue Crack Tip Under Cyclic Loading with Constant Stress Intensity Factor

O. Plekhov, A. Vshivkov and A. Iziumova

Introduction

Fatigue crack propagation in metals is one the important problems of fracture mechanics. During pretty wide range of crack rates the kinetics of a crack growth can be described by correlation with a value of current stress intensity factor (Paris's law). This correlation is the result of the approximation of many experimental data and doesn't explain the physical nature of this process. Many authors proposed other correlations of the fatigue crack rate and different mechanical-structural parameters. For instance the J-integral, the work of plastic deformation, the size of the zone of a plastic deformation, the amount of dissipated energy were used as a parameter determining the crack propagation rate [1, 2].

The infrared thermography has been considered as a most effective method for estimating of the power of the heat sources in the process of mechanical testing. The main problem of application of this technique to the study of heat dissipation is caused by the uncertainty of solution of inverse problem. The principal solution of the problem of determination of energy dissipation under deformation can be obtained by the development of the additional system for direct monitoring of a heat flow. Such system based on the Seebeck effect was developed in ICMM UB RAS [3]. The system allows one to carry out quantitative measurements of a heat flow from the deformed sample within an area given by the dimensions of the used Peltier element.

The previous study of the authors was focused on crack growth problems under constant stress amplitude [3]. The experiments with constant stress intensity factor for the first time were reported in [4]. It has been shown that heat dissipation measured by contact heat flux sensor decreases during the crack propagation with the constant stress intensity factor.

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To propose a theoretical explanation of this effect we derived an equation describing the evolution of plastic work at the crack tip. Following by the idea [5] we divided the plastic work and, as a consequence, heat dissipation at crack tip into two parts corresponding to reversible (cyclic) and monotonic plastic zones. Analysis of this approximation has shown the independence of heat dissipation in cyclic plastic zone from the crack advance. The dissipation in monotonic plastic zone is a function of both crack rate and characteristic diameter of the yield surface and gives well know correlation between fatigue crack rate and dissipated energy [3].

To confirm the proposed approximation we compare it with the results of fatigue crack propagation test in flat samples made from stainless steel AISE 304. The obtained results are in a qualitative agreement with the experimental data.

Experimental Setup

A series of samples made from stainless steel AISE 304 were tested. The detailed description of mechanical properties, geometry of the samples and test conditions are presented in [3, 4]. The samples were subjected to cyclic loading of 20 Hz with the constant stress intensity factor and loading ratio $R = -1$.

To analyze the dissipated energy at the crack tip a contact heat flux sensor was designed and constructed. The detailed description of the sensor is presented in [3]. 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 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. A thermal contact between the sample and the sensor is provided by the introduction of the thermal paste. These sensors were calibrated using a device reproducing the sample under study with a controlled heat flux.

The experimental program includes four tests with the constant stress intensity factor. The constant stress intensity factors are equal of 15, 17.5, 20, 22.5. The crack rates were 2.0076, 6.6391e−08 m/cycle, 1.0245, 1.7177e−07 m/cycle, correspondingly. Each experiment includes first part with constant stress amplitude to initiate the fatigue crack with the length of 1 mm and the second part with the constant stress intensity factor which was kept up to the 8 mm crack length.

It is important to note that similar experimental program was realized in ICMM UB RAS. The detailed description of mechanical properties, geometry of the samples and test conditions are presented in [3]. The similar steel (Russian analog) with different sample geometries was tested with the loading ratio $R = 0$. The stress intensity factors were equal to 25 and 30 MPa $m^{1/2}$ (for crack rates of 1.4, 1.65e−07 m/cycle, correspondingly). The results of the both experimental programs are.

Results of Fatigue Experiments

The typical results of the test are presented in Fig. 1.

The test includes stress amplitude part up to 2200-th second. We can observe the stable accelerated crack propagation from 500-th to 2200-th second of the test accompanying by the increase of the heat dissipation. Form 2200-th second the stress intensity factors was kept constant. It leads to the decrease of the stress amplitude (Fig. 1a) and heat dissipation and nearly uniform crack propagation (Fig. 1b).

Theoretical Analysis of the Heat Dissipation

Following the idea proposed in [5], we can start from a relation between elastic and real deformation at the crack tip:

$$\varepsilon_{\mathrm{ij}}^{ef} = (G/G_s)^{\frac{1}{2}}\varepsilon_{ij}^{el}, \tag{1}$$

where G—the shear modulus, G_s—secant shear modulus.

Equation (1) was originally proposed by [7] as a result of photo elastic experiment data treatment. Using the Ramberg-Osgood relation $\gamma = \tau/G + A(\tau/\tau_0)^n$, we can write a following estimation for octahedral stress and link it with an elastic solution

$$\tau_{oct} = \tau_{oct}^{el}\left(3 + 2(1+\nu)B\xi^{n-1}\right)^{\frac{1}{2}} \Big/ 3\left(1 + B\xi^{n-1}\right), \tag{2}$$

where A, τ_0, n—material constants, $B = GA/\tau_0(\tau_e/\tau_0)^n$, $\xi = \tau_{oct}/\tau_e$, τ_e—elastic limit.

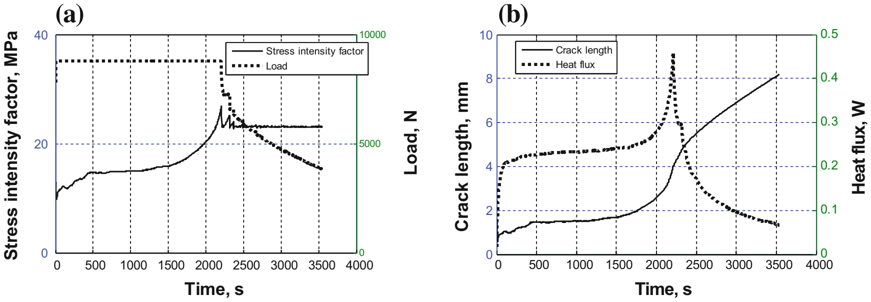

Fig. 1 The stress intensity factor and applied load (**a**), heat dissipation and crack length (**b**) histories during the whole test (The experiments were carried out at Bundeswehr University Munich)

To analyze plastic deformation at the crack tip under cyclic loading we need to divide energy dissipation in cyclic and monotonic plastic zones at the crack tip $U_p^{tot} = U_p^{cyc} + U_p^{mon}$.

The energy of representative volume at cyclic zone can be estimated as

$$U_p^{cyc} = 3/2\tau_{ec}\gamma_{pc}, \tag{3}$$

where τ_{ec}—characteristic size of the yield surface, γ_{pc}—amplitude of plastic deformation under an assumption of the validity of Ramberg-Osgood relationship, $\tau_{oct,c}$—stress change in the representative volume.

The full energy of cyclic plastic zone can be calculated as a double integral over the region (S) bounded on the outside of the monotonic plastic deformation zone and inside of the fracture zone

$$U_p^{cyc} = \int\limits_S \int\limits_0^\pi 3\tau_{ec}^2\left(G_S^{-1} - G^{-1}\right)\left(\tau_{oct,c}/\tau_{ec} - 1\right) r dr d\theta. \tag{4}$$

The simple approximation of cyclic-monotonic plastic zone boundary can be given by $r = r_{p,c}f_e, for$ cyclic-fracture zone boundary—$r = r_{p,c}f_e\tau_{ec}/\tau_{fr}$.

The energy increment in cyclic plastic zone can be written as

$$dU_p^{cyc}\Big/dN = 3\tau_{ec}^2\left(G_S^{-1} - G^{-1}\right)\int\limits_S \int\limits_0^\pi d\tau_{oct,c}\Big/d\tau_{oct}^{el} d\tau_{oct}^{el}\Big/dN r dr d\theta \tag{5}$$

The direct calculation of Eq. (5) gives $dU_p^{cyc}\Big/dN = 0$. It means that dissipation in cyclic plastic zone doesn't depend on the crack advance and fully determined by the applied load.

The energy dissipation in monotonic plastic zone can be estimated as $U_p^{mon} = 3/2\tau_e\gamma_p$. The energy increment per one cycle can be written as

$$dU_p^{mon}\Big/dN = 3\tau_e\left(G_S^{-1} - G^{-1}\right)\int\limits_{S_1} \int\limits_0^\pi \tau_{oct} d\tau_{oct}\Big/d\tau_{oct}^{el} d\tau_{oct}^{el}\Big/dl dl/dN r dr d\theta \tag{6}$$

Solution of (6) for the case of $dr_p/dl \to 0$ presented in [5].

For the following analysis it is important that $dU_p^{tot}\Big/dN$ is a function of crack rate (dl/dN). Finally, Eqs. (5) and (6) allows us to propose the following approximation for energy of plastic deformation at the fatigue crack tip

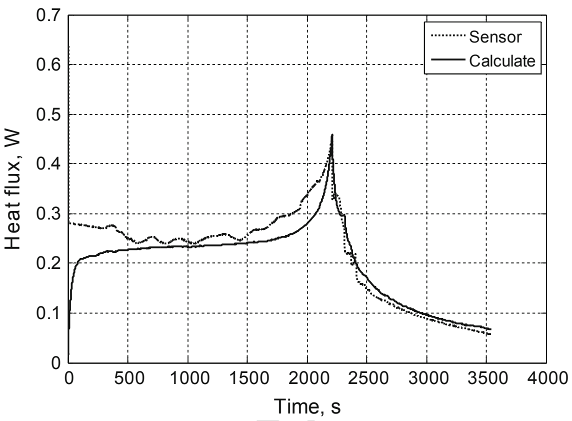

Fig. 2 Heat dissipation histories during the test carried out under constant stress amplitude (up to 2200-th second of the test) and constant stress intensity factor (remaining time) (Solid line— approximation (7), the dotted line—experimental results)

$$dU_p^{tot} \Big/ dN = W_1\left(A_\tau^2, r_p\right) + W_2\left(A_\tau^2, r_p\right) dl/dN = a_1 A_\tau^2 + a_2 A_\tau^2 dl/dN, \qquad (7)$$

where A_τ—applied stress amplitude which determines the diameter of yield surface.

The process of heat dissipation is determined by the plastic work. This relation could be complex due to the peculiarities of energy storage in material structure but taking into account the simplicity of Eq. (7) we will use the linear dependence of heat dissipation versus energy of plastic deformation for the first approximation of experimental results.

Figure 2 presents the comparison of approximation (7) and results of the contact heat flux sensor. Equation (7) gives a good qualitative description of peculiarities of heat dissipation in both regimes with the constant stress amplitude and constant stress intensity factor. For constant stress amplitude the plastic work and, as a consequence, energy dissipation at the crack tip is determined by crack rate as is shown [2] but for constant crack rate we can observe the regimes with the decrease of the heat dissipation caused by the decrease of the applied stress amplitude.

Conclusion

In this work the experimental and theoretical study of energy dissipated at fatigue crack tip in AISE 304 steel were carried out. The experiments include two regimes of crack propagations: constant stress amplitude and constant stress intensity factor. It has been experimentally shown that for constant stress amplitude we can observe the increase of the heat dissipation correlated with the fatigue crack tip. The crack propagation with the constant stress intensity factor is accompanied by the decrease of the heat dissipation. This effect was observed independently in two different experimental programs.

To propose one of the possible explanations for the observed results a theoretical analysis of plastic work at fatigue crack tip taking into account the evolution of both monotonic and cyclic plastic zones has been carried out. This analysis allows us to propose a simple approximation for the heat dissipation at fatigue crack tip. The theoretical results give a good qualitative description of peculiarities of the heat dissipation in both regimes with the constant stress amplitude and constant stress intensity factor. For the constant stress amplitude the plastic work and, as a consequence, energy dissipation at the crack tip is determined by the crack rate but for the constant crack rate regime the scenarios with a drop in the heat dissipation takes place.

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