THERMAL "SELF-ARREST" OF A CRACK DURING FRACTURE: MULTI-ARREST MODES

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The study of the dissipation effects during fracture of elastic bodies represents a significant interest from both fundamental and applied viewpoint. An establishment of quantitative balance between the energy influx to the destruction zone from external sources, and the energy liberated at fracture taking into account self-heating effects during fracture and their influence on the fracture dynamics is not yet solved problem of the theory of fracture. Meanwhile, heating effects arising at deformation and fracture of macrobodies as a result of dissipation processes of the various nature (plastic and/or viscoelastic deformation of a material, internal friction, etc.) can essentially modify physical properties of a material (through corresponding heat-flux related parameters) and moreover may appreciably affect the dynamics of fracture.

Let us consider thin plate containing a tensile crack of the size $2a$, affected by stretching pressure p. It is well-known that the plastic-deformation zone (of size d), located just at the crack tip, provides a stabilizing role, since effectively absorbs a part of the elastic energy allocated at disclosing of a crack. Meanwhile, the plastic deformation of a material expressing an irreversible redistribution of dislocations in a plastic zone, is accompanied by the intensive energy dissipation which results in the local heating of the near-crack-tip zone.

Elastic energy $\delta U = \lambda p^2 a \delta a h / E$ released during crack extension by δa (E being the Young modulus and λ is the geometry-related factor) goes to the formation of new faces of a crack $2\gamma\delta a h$ (γ -surface energy, h – the cross-section size of a plate) and partly to the work of plastic deformation $G_0 a \delta a$ which then transfers to heat. When the elastic energy liberation rate surpasses a gain of surface energy and plastic work, the crack starts to propagate. Thus, the condition of stability may be written down as:

$$\lambda p^2 a + F < 2\gamma + G_0 a \tag{1}$$

where F is the crack-extension driving force. In order to consider nonisothermal crack propagation process self-consistently one needs to describe thermal field near the crack. The analysis of temperature concentration near the crack tip requires the solution of a thermal problem. The effect of thermal "arrest" of the crack represents the phenomenon when the locally heated crack abruptly stops due to the plastic-work related dissipation, so that condition (1) is met. This phenomenon was observed in a number of recent experiments, however its theoretical description is not as yet completed.

To study the crack-growth dynamics with the account for the energy dissipated near the crack tip zone requires to solve jointly the equation of motion of a crack and the equation of heat conduction. The system of the equations governing both temperature and crack-size evolution reads:

$$\begin{aligned} C_v \dot{T} a^2 \varphi(p) &= G_0 \dot{a} a - W a \psi(p)(T - T_0) \\ 2a^2 \mu \ddot{a} + 2\mu a \dot{a}^2 - \frac{\lambda p^2}{E} a &= -2\gamma(T) - G_0 a + F(t) \end{aligned} \tag{2}$$

here $\psi(p)a$ and $\varphi(p)a^2$ represent the perimeter and the area of a plastic zone, respectively, T is an average temperature of the crack-tip zone, Cv being thermal capacity of a material, μ is the Mott parameter (which is calculated in the quasistatical approach) describing kinetic energy of a crack.

For the analysis of system of the equations (2) in the non-dimensional variables we approximate functions $\gamma(T)$, $G(T)$, $\psi(T)$ and $\varphi(T)$ by the following expressions:

$$\gamma(T) = \gamma_0\left[1 - (T-T_0)/T_1\right], \qquad G(T) = G_0\left[1 + (T-T_0)/T_2\right],$$
$$\varphi(p) = \varphi_0\left[1 + (T-T_0)/T_3\right], \qquad \psi(p) = \psi_0\left[1 + (T-T_0)/T_4\right]$$

Let introduce non-dimensional variables: $y = a/a_0$ $\Theta = (T-T_0)/T_0$, $\tau = t/t_0$

where a_0 - the characteristic size of a crack. Here T_0 is the temperature of the environment, which corresponds to the isothermal fracture condition, provided $\Phi/G < 1$, and t_0 is the characteristic time of the problem ($t_0^2 = \mu a_0^3/\gamma_0$). The parameters which are included in system (2) are defined as follows:

$$\alpha_i = T_0/T_i \quad \beta = (\Phi_0 - G_0)\,a_0/\gamma_0 \quad g = G_0T_0/C_v\varphi_0, \quad f = F/\gamma_0$$
$$\eta = \left(B/\gamma_0\right)\left(\gamma_0/\mu a_0\right)^{1/2n}, \quad W_1 = \left(W_0\xi_0/C_0\varphi_0\right)\left(\mu_0 Q_0/\gamma_0\right)^{1/2}$$

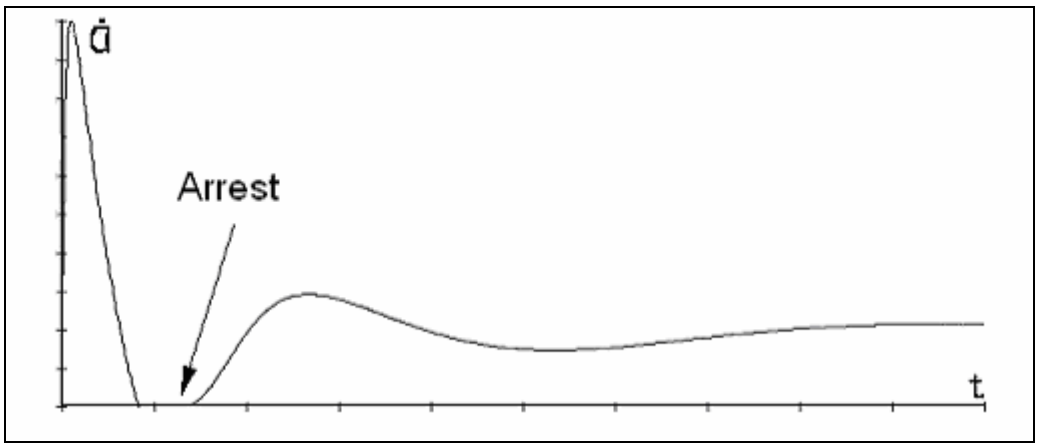
With the account for the above notations the non-dimensional system of the evolutionary equations (2) is written down as follows:

$$\frac{d}{d\tau}(y^2\frac{dy}{d\tau}) - y\dot{y}_\tau^2 = \beta y + \Theta(\alpha_1 - \alpha_2 y) - \eta(\dot{y}_\tau)^{1/n} + f - 1$$
$$(1+\alpha_3\Theta)\,y\dot{\Theta}_\tau = g(1+\alpha_2\Theta)\,\dot{y}_\tau - W_1(1+\alpha_4\Theta)\Theta \qquad (3)$$

Crack arrest conditions

Results of the numerical solution the system (3) are presented below. The following conditions are assumed: $y(0)=1$, $\dot{y}(0)=0$, $\Theta(0)=0$, reflecting the initial condition (at $t=0$) of the static and not heated crack . The time dependencies of dimensionless crack velocity and its local temperature $\dot{y}(\tau), \Theta(\tau)$ are shown in fig. 1 a, b.

a)



b)

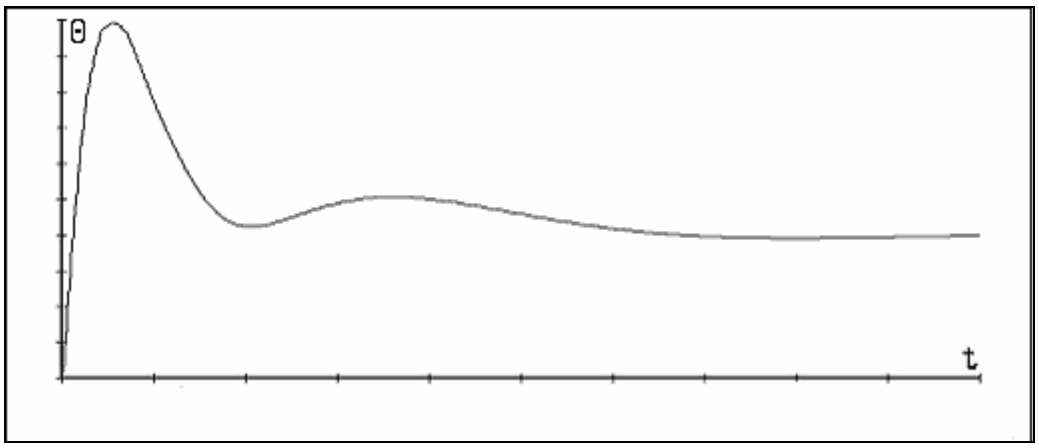


Figure 1. The dependences $\dot{a}(\tau), \Theta(\tau)$ obtained at fixed values of parameters: $\alpha_1 = 1$, $\alpha_2 = 1, \alpha_3 = 0, \alpha_4 = 0, W_1=0.5, \beta = 1, g = 1, \eta = 0, n = 1, f(\tau) = const = 3$.

It is seen from Fig. 1 that the crack suffers only one stop (1 arrest) during propagation, and the peak of local temperature is reached near the point of the crack stop. The minimum of local temperature coincides with the moment of an exit of a crack from arrest; this tendency is observed for the multi-arrest case as well. Note that during arrest thermal subsystem is the only relaxing part of the entire system. This relaxation provides an efficient heat transfer from the warmed up crack-tip zone. As it is apparently seen from figure 1a, after rather long time, the temperature and growth rate of a crack reach some stationary values, which may be derived from the balance of local heating and a heat-conduction process.

It is seen, that the "arrest" has a finite duration time Δt_a. We discovered that key parameters which determine the duration of the arrest are as follows: the cooling intensity W_1, , plastic response constant α_2, and the crack- driving force *f*. In fig. 2 the dependence is shown of the first "arrest" duration time on the cooling constant W_1 (varying from 0 up to 1). Results are obtained under initial conditions $a(0) = 1$, $\dot{a}(0) = 0$, $\Theta(0) = 0$ for the following values of the system parameters: $\alpha_1 = 1$, $\alpha_2 = 1$, $\alpha_3 = 0$, $\alpha_4 = 0$, $f = 3$, $\beta = 1$, $g = 1$, $\eta = 0$, $n = 1$.

Apparently it is seen from the Figure 2, that there are values W_1 when no "arrest" is observed. This is due to the high enough heat conduction from the crack tip zone; therefore the crack is not capable to save up a sufficient amount of energy for the stop. As it is observed at $W_1 \geq W_M$, thus there is value W_1 when "arrest" is impossible.

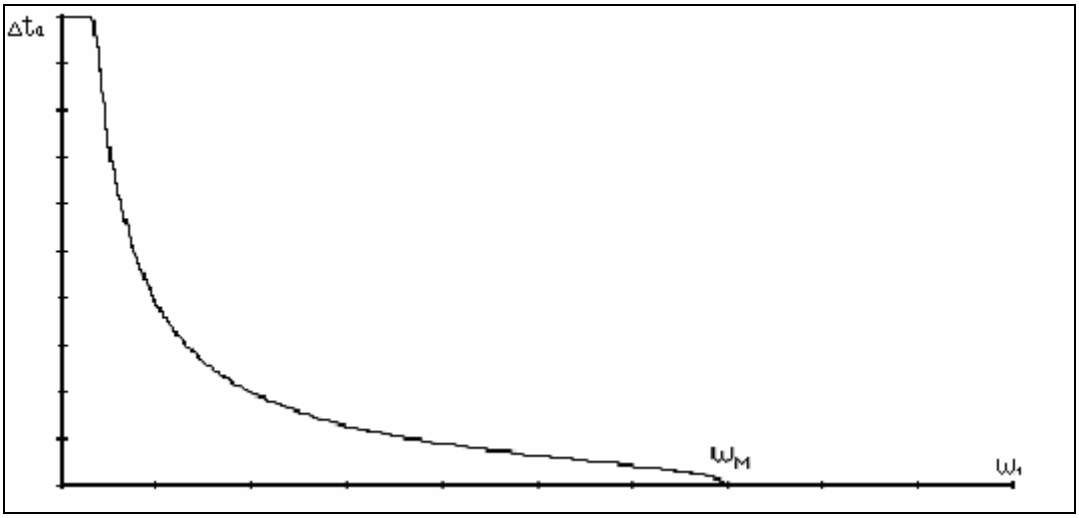


Figure 2. Dependence of the first "arrest" duration on the parameter W_1.

Let us consider the influence W_1 and α_2 on the number of "arrests". For this purpose we shall construct the "arrest" diagram (see Fig. 3). In the coordinate plane W_1 and α_2 the areas with different number of "arrests" are designated. I our calculations we assumed W_1 varying from 0.1 up to 2.0, and α_2 varying from 1.0 up to 5.0.

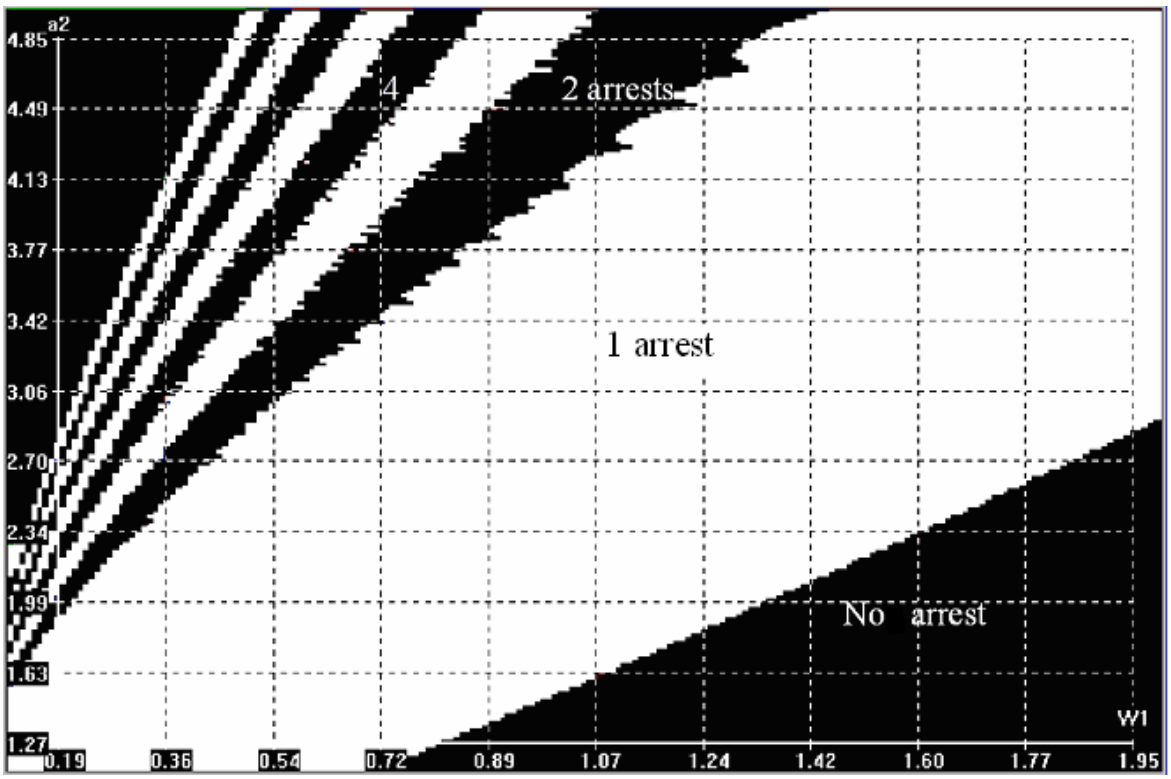


Figure 3. The crack "arrest" diagram .

From the diagram well defined borders are seen of the "arrests" number quantity . Reduction of number of "arrests" with the increase of W_1 and increase in their number with growth of parameter α_2 may be explained by the heating conditions at the crack tip.