Thermo-Mechanical Effect and Criterion of Crack Propagation

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ABSTRACT: *A thermo-mechanical effect from partial conversion of fracture work into heat energy during crack propagation is considered with a simple mathematical model. It is assumed that the heat production zone in the vicinity of the crack tip is very small. Thus, the crack propagation process can be viewed as propagation of the crack in elastic material with a point thermal heat source fixed at the tip of the crack. This thermal heat source generates its own temperature and stress fields around the crack tip. It also generates a negative stress intensity factor that specifies fracture mode I and has to be accounted for in the energetic fracture criterion. The model developed may help to explain many experimental observations such as the increase in the specific surface energy that accompanies an increase in the crack speed and why fracture mode I has a special role in crack propagation phenomena.*

INTRODUCTION

Conversion of inelastic work, in particularly work of plastic deformations into heat, has been reported many years ego by Taylor and Quinney [1]. A large body of experimental and theoretical work has been dedicated to the thermal effects. In brittle materials with very small plastic zones and high crack velocities, the temperature rise is predicted to be higher than 1000 K [2]. Experimental evidence of the significant temperature rise during fracture can be found for example in [3] and [4]. Zehnder and Rosakis [5] have employed high speed, high resolution, and non-contact infrared sensors to detect the temperature rise during rapid crack growth in 4340-carbon steel. In their initial experiments, they measured a temperature rise of about $450\,^0C$ close to the crack tip. It seems the highest temperature rises were detected during fracture of very brittle materials such as glass and quartz. For the detecting of high local temperatures the light intensity emitted during fracture was compared with the normalized black body radiation. Temperatures between 2500 and 3000 K are measured for glass and about 4000 K for quartz, respectively [2].

In many papers it has been suggested that the thermal effects may participate in the governing of fast running cracks and may be responsible for many experimentally observed phenomena. These include the reasons for the increase of the specific surface energy with increase of the crack speed, existence of the limiting crack speed that is approximately half of theoretical predictions, branching and so on [6]. However, only few trials to solve both the mechanical and thermal problems have ever been attempted [7] and [8]

In this paper, probably the simplest theoretical model incorporating the thermo-mechanical effects at crack propagation with linear fracture mechanic concept is developed. A fracture criterion based on analytical solutions following from this model is proposed and some sequences of the model and analytical results obtained are discussed. It is believed that this simple model can help in setting the right goals for further experimental investigations.

MODEL

Consider the propagation of a semi-infinite crack with a constant velocity v. Let the heat production zone in the vicinity of the crack tip be small enough so that the crack propagation process is controlled by the stress intensity factor(s) $K_{I,II,III}$ calculated for a linear-elastic material [9]. As it is well known the fracture work associated with the formation of new surfaces is determined mainly by the work of inelastic deformations and irreversible processes. This work depends on the material, the temperature and the crack velocity, and it is usually 3 or 4 orders of magnitude higher than the free-surface energy.

A considerable proportion of the fracture work is dissipated as heat, this being nearly 90 per cent in metals and 60-80 per cent in polymers [2]. The rest of the fracture work is stored in the form of a modified atomic/molecular/grain structure in the vicinity of the crack tip. Thus, with the above assumption, the crack propagation process can be viewed as the propagation of the crack with a point thermal heat source fixed at its tip. The power of the thermal heat source can be calculated as

$$q = \beta G v \tag{1}$$

where the factor β express the fraction of the fracture work converted into heat, G is the specific fracture work and v is the velocity of the crack tip. Equation (1) will also hold for very brittle materials such as glass and quartz [2] where the factor of conversion β is close to 0.5.

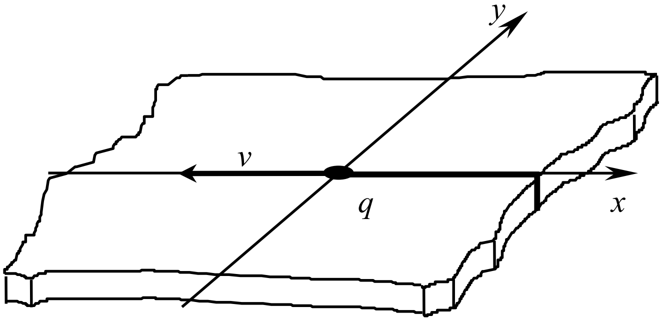

Fig.1 Coordinate system

In reality, of course, the thermal heat source has its own size, and some density of the heat power is distributed inside the heat production zone. The thermal problem for more complex (finite) shapes of the heat-production zone at crack propagation such as a circle and a rectangle has been considered before by Weichert and Schonert [2] however these shapes make further analysis too cumbersome. Moreover elastic analysis of the mechanical models with a finite heat-production zone becomes self-contradictory because the finite shape of the heat production zone suggests that inside this zone the deformations are non-elastic.

It is clear that the heat source will generate its own temperature field in the vicinity of the crack tip. This temperature field can also lead to additional thermal stresses localized in the vicinity of the crack tip that in turn can change the stress-state in this area and affect fracture-controlling parameters such as stress intensity factors. This mechanism will be referred to as the thermo-mechanical effect associated with crack propagation.

Within assumptions made above the value the thermal stress intensity factor can be found as [10] and [11]

$$K_I^T = -\frac{2\beta G v \mu m}{\pi \kappa \sqrt{\lambda}} \tag{2}$$

where μ is the shear modulus, $\lambda = \frac{v}{2D}$; κ is the thermal conductivity, D is the thermal diffusivity, $m = (1+\nu)\alpha$ for plane stress and $m = \frac{1+\nu}{1-\nu}\alpha$ for plane strain; α is the linear expansion coefficient, ν is the Poisson's ratio.

As can be seen from formula (2) the stress intensity factor is negative. Consequently, this formula (2) has a sense only if surfaces of the cut (crack) do not contact each other, either due to external forces or due to others reasons (the crack is fully open). Now we consider the dynamic fracture criterion taking into account the thermal stress intensity factor induced by the crack propagation and the thermo-mechanical effect.

CRITERION FOR CRACK PROPAGATION

As it is well known the classical dynamic fracture criterion expressing the energy balance equation can be written as follows [12]

$$G = \frac{1}{2\mu}\left\{\frac{v^2}{c_2^2 R}\left[\delta_1 K_I^2 + \delta_2 K_{II}^2\right] + \frac{K_{III}^2}{\delta_2}\right\} \tag{3}$$

$$R(\delta_1, \delta_2) = 4\delta_1\delta_2 - \left(1+\delta_2^2\right)^2 \text{ and } \delta_{1,2}^2 = 1 - \left(v/c_{1,2}\right)^2$$

where c_1 is the speed of longitudinal waves, c_2 is speed of dilatational waves and R is the Rayleigh's function.

Now we consider a modified fracture criterion that takes into account the thermo-mechanical effect associated with crack propagation. For $K_I + K_I^T \geq 0$ the fracture criterion taking into account the crack closure due to the thermal stress intensity factor can be written as

$$G = \frac{1}{2\mu}\left\{\frac{v^2}{c_2^2 R}\left[\delta_1\left(K_I + K_I^T\right)^2 + \delta_2 K_{II}^2\right] + \frac{K_{III}^2}{\delta_2}\right\} \tag{3}$$

where the thermal stress intensity factor K_I^T can be calculated using formulae (2) from which as it is shown $K_I^T < 0$. Because the thermal stress intensity factor is negative it works against the fracture process by reducing the effective stress intensity factor for mode I ($K_I^{eff} = K_I + K_I^T$). This is also in a correspondence with general thermodynamics principles, which determine a response of a thermodynamic system to internal or external disturbances. In accordance with these principles the response of thermodynamic system should compensate such disturbances.

On Fig. 2 a comparison of experimental data for aluminum [13] with the theoretical prediction is presented. The aim of this comparison is not to achieve a numerical correlation with experimental data but is to show that the thermo-mechanical effect under consideration is relevant to the fast crack propagation phenomenon; that is, it has the same order of values as the increase of the specific surface energy. In addition, as it can be seen from these figures, this effect alone can describe the initial increase of the specific surface energy (or dynamic stress intensity factor) with an increase of the crack propagation velocity. However, as it is readily seen from these figures at larger crack propagation velocities this effect alone cannot explain further increase of the specific surface energy.

From the theoretical model developed it follows that fracture mode I has a special role in crack propagation phenomenon. For a stable crack propagation mode I opening must be present and a value of the corresponding stress intensity factor should be more than the value of the thermal stress intensity factor. Experimental observations of dynamically curving cracks under mixed-mode loading also confirm this conclusion [14] and [15]. Cracks were observed to propagate along a straight line under mixed-mode loading (see for example [15]) in contrast to the dominant fracture mode II. The presence of the mode I type of crack propagation ensures the fracture mechanism with the lowest energy requirement for crack propagation. This may explain why under mixed-mode or pure mode II loading, the crack will quickly find the path along which the local conditions of the mode I type [16]. Thus, there are quantitative and qualitative reasons for the modification of the classical dynamic fracture criterion to include the thermal stress intensity factor.

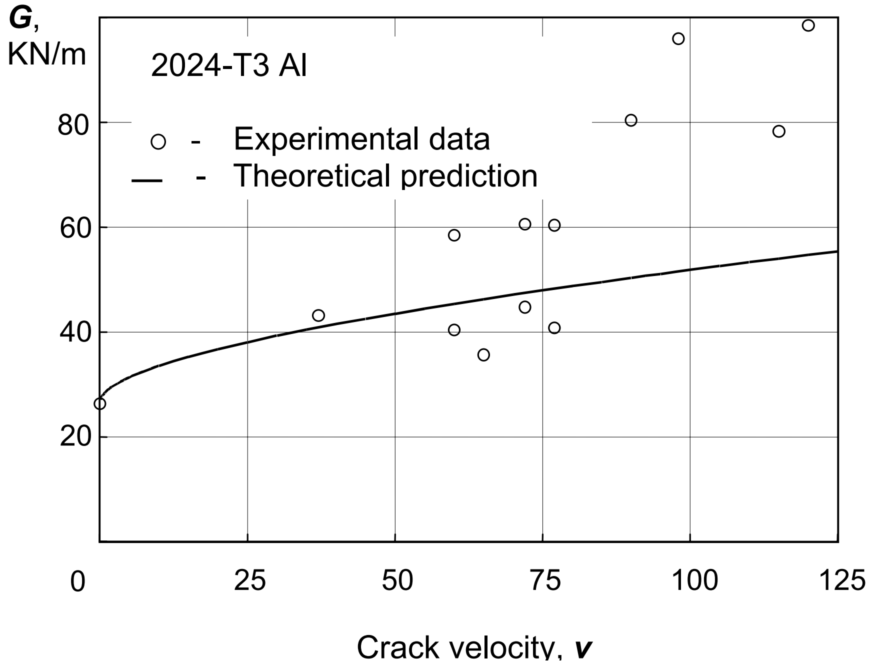

Fig.2 Comparison of experimental data for specific surface energy [13] with theoretical prediction

CONCLUSION

Because the characteristic length of the thermo-mechanical effect at fast crack propagation $(1/\lambda)$ is typically very small in comparison with other dimensions, the obtained solution can be applied to problems with finite geometry and in the case of non-steady fast crack propagation. As it can be seen from formulae (2) as soon as the speed of the crack is approaching zero, all thermo-mechanical effects become negligible. Meanwhile for fatigue loading, the effective power of the heat source will be determined by work of irreversible processes taking place at one cycle multiplied by the frequency of the loading. The summing effect may be rather significant and may affect the crack [17].

There are other mechanisms participating in the crack propagation phenomena. These may be visco-plasticity mentioned above, cohesive mechanisms effecting the crack face interaction in the vicinity of tip, damage mechanisms connected with the formation of micro-cracks, voids around the crack tip and mechanisms responsible for the formation of the surface roughness that effectively increases the area of the fracture surface. On the one hand, the investigation of each of these experimentally is an extremely difficult problem. On another hand it is very difficult to explain the crack behavior considering only one of them. So, it is very important to develop theoretical model and investigate effects from each mechanism keeping in mind the global goal to incorporate them into a general model to predict crack growth behavior.

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