Light emission from the tip of stationary and moving cracks.

Ståhle, P.

1988

Document Version:
Förlagets slutgiltiga version

Link to publication

Citation for published version (APA):
Ståhle, P. (1988). *Light emission from the tip of stationary and moving cracks.* (UPTEC). Institute of Technology, Uppsala University.

Total number of authors:
1

Light emission from the tip of stationary and moving cracks

Progress report

by

P. Ståhle

Light emissions from the tip of stationary and moving cracks in a brittle steel.

Introduction

A project with the intention to employ the emitted light from a running crack tip has just recently been initiated. So far only the preparations and planning has been executed. The background of the project is as follows.

The importance of considering the process region characteristics at fracture mechanics analyses is recognized by an increasing part of the scientific community. It seems reasonable that the property of consuming energy at crack growth must be ascribed to the process region. Due to mathematical convenience the process region is often assumed to the point sized which has the undesired consequence that one does not obtain any energy flow to the process region to account for the fracture processes when using common rate independent material models such as perfectly plastic linearly hardening or powerlaw-hardening materials. The obvious way of avoiding these difficulties is to consider spatial extension of the process region.

At an on going STUF-sponsored investigation the process region is modelled as a line shaped cohesive zone (see fig. 1). The physical properties of the model is given by a relation between the cohesive stress and the separation of the cohesive zone surfaces. The relationship might f. i. be given by a diagram such as the one in fig. 2. We note that the energy consumed in the cohesive zone is represented by the area below the curve $\sigma_y=\sigma_y(v)$ (see fig.1 for notations). The distribution of plastic strain in the remote parts of the plastic zone is fairly well understood through numerical studies. The amount of energy consumed in the process region is not known and further the relation between and surface energy is not known. Most of the plastic work is likely to leed to heat after a very short period of time, related to the lattice time period which normally is of the order 10^{-10} - 10^{-14}.

In order to observe emission of light from the crack tip neighbourhood a simple experiment was performed. Such emission has earlier been observed from cracks in quarts [1]. A three point bend specimen was slowly loaded. The load was applied so that sparks from friction at the loading device was avoided (see fig. 3). As the experiment was performed in "total" darkness a photomultiplicator registered very few photons before the test was started. As the load was applied emission of photons was registred during the slow crack growth. As much ass 20 to 100 times the background radiation was registred. The experiment was repeated several times with identical results.

In an attempt to explain the emission of photons a crack in a perfectly plastic material is studied.A mode III crack is studied for its mathematical simplicity.The process region is here assumed to be point shaped.

For the stationary mode III crack (see fig. 4) at small scale yielding, the plastic strain γ_p is given as follows:

$$\gamma_p = \frac{k_{III}^2}{\pi\tau_Y G}\,\frac{\cos\theta}{r} - \frac{\tau_Y}{G} \quad \text{for } \gamma_p > 0 \tag{1}$$

where τ_Y is the shear yield stress, G is the elastic modulus at shear and K_{III} is the stress intensity factor. The polar coordinate system r, θ is attached to the crack tip.

If we assume that a) all plastic work is transformed to thermal energy [2] and b) the load is applied sufficiently fast so that the process can be assumed to be adiabatic outside a distance r_0 from the crack tip. Then the temperature distribution T is easily calculated from the calorimetric formula

$$\frac{dW}{dm} = \frac{\tau_Y \gamma_p}{\rho} = cT \tag{2}$$

where dW/dm is the plastic work per unit of volume, ρ is the mass density and c is the heat capacity per unit of volume. One obtains the following

$$T = \frac{\tau_Y^2}{c\rho G}\left(\frac{2R_p}{r}\cos\theta - 1\right) \quad \text{for } T > 0 \tag{3}$$

where $2R_p$ is the linear extension of the plastic zone straight ahead of the crack tip. R_p is given by

$$R_p = \frac{1}{2\pi}\left(\frac{K_{III}}{\tau_Y}\right)^2 \tag{4}$$

For a typical steel with c =460Ws/kgK, ρ =7800kg/m^3 and τ_Y=100MPa, the result is a surprisingly low temperature in the major part of the plastic zone, e.g. the temperature is 7 K at $r=10^{-2}R_p$ and 700 K at $r=10^{-4}R_p$ Note that it is assumed that $r<r_o$. In order to check the validity of the assumption of adiabatic processes for $r>r_o$ we use the governing equation for transient heat conductivity

$$\frac{\partial T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2} = \frac{c\rho}{\lambda}\frac{\partial T}{\partial t} \tag{5}$$

The relative temperature rate dT/(Tdt) is obtained as

$$\frac{dT}{Tdt} = -\frac{3\lambda}{c\rho r^2}\left(1 - \frac{r}{2R_p \cos\theta}\right)^{-1} \qquad (6)$$

For an example we choose a rise time Δt for the remote load and assume, to simplify the calculations, small values for $r_o \cos\theta$. The following value for r_o is estimated

$$r_0 = \left[\frac{3\lambda T}{c\rho(dT/dt)}\right]^{\frac{1}{2}} \qquad (7)$$

It seems reasonable to put the largest acceptable value for dT/(Tdt) equal to $0.1/\Delta t$ for an adiabatic process. For a typical steel (λ=45W/mK) we obtain r_o=0.6mm. This result implies that a rather large region around the crack tip cannot be considered as adiabatic.

Instead we assume, rather roughly, that a region in which say dT/(Tdt)>$10^3/\Delta t$ (i.e. $r<r_o$ is isothermal. Then within the frame work of the model assumed the temperature for $r<r_o/100$ is given by the average over the area $r<r_o/100$ and $-\pi/4<\theta<\pi/4$ i.e.

$$T = \frac{400}{\pi}\,\frac{\tau_Y^2}{c\rho G}\,\frac{R_p}{r_0}\,. \qquad (8)$$

With G=80GPa and R_p=5 mm the temperature equals 36 K (which of course should be understood as a temperature of 36K above an environmental temperature of say 20°C, i.e. T=56°C.

As regards the observed emission of photons 56°C is a very low temperature. The peak intensity would be for a photon energy of 0.2 eV. In the sensitive region for the standard photomultiplicator used, the total emitted photons are very few . Thus the distinct emission that actually was registered can hardly be explained by the temperature rise alone.

One explanation can be that the plastic straining involves processes responsible for the radiation. Another possibility is that such processes are located inside the process region, which was not considered in the analyses above. Even radiation after excitation by mechanically induced electrones might be possible (cf. [3]).

We believe that further research is urgently needed. We also believe that a study of the light spectra and intensity emitted from stationary and running cracks might provide information regarding the dependence of the fracture processes on conditions such as crack propagation rate and environmental factors. Further the possibilities of employing the effects for crack tip speed measuraments ought to be investigated.

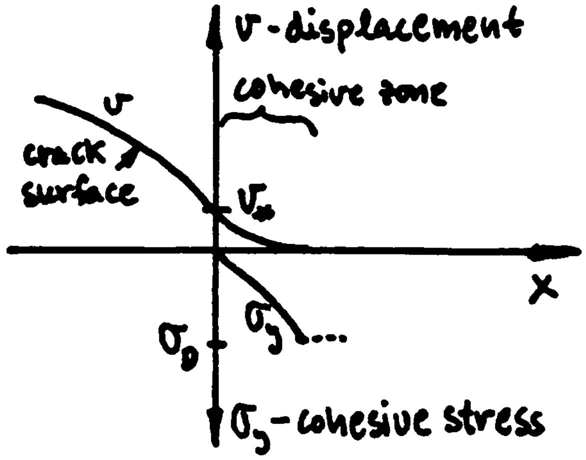

Fig.1.Stress and displacement in the cohesive zone.

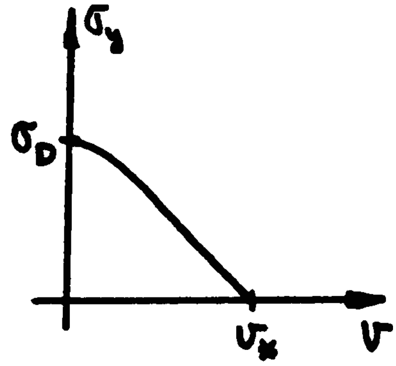

Fig.2. Stress-displacement relationship.

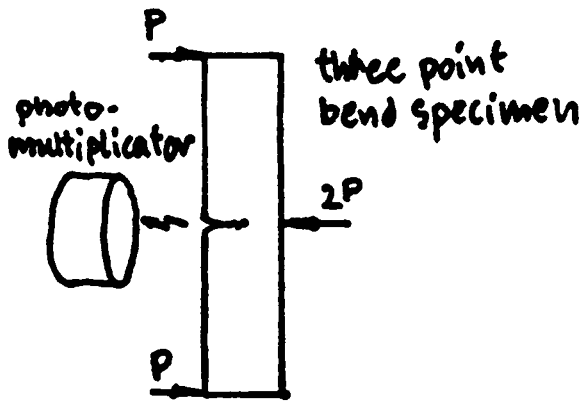

Fig.3. Principal view of the radiation experiment.

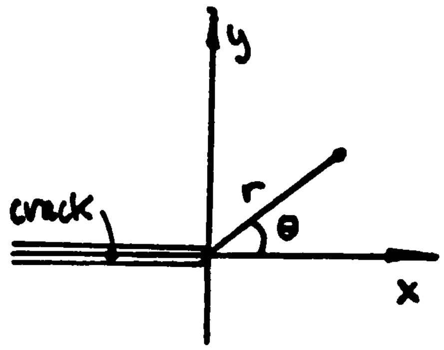

Fig.4.The polar coordinate system attached to the crack tip.

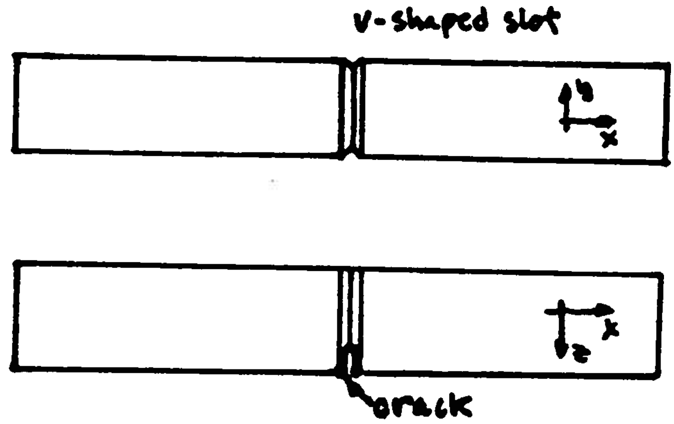

Fig.5. The modified three point bend specimen.

Light emission from the tip of stationary and moving cracks

Project proposal

by

P. Ståhle

Light emissions from the tip of stationary and moving cracks in a brittle steel.
Project proposal.

Introduction

The importance of considering the process region characteristics at fracture mechanics analyses is recognized by an increasing part of the scientific community. It seems reasonable that the property of consuming energy at crack growth must be ascribed to the process region. Due to mathematical convenience the process region is often assumed to the point sized which has the undesired consequence that one does not obtain any energy flow to the process region to account for the fracture processes when using common rate independent material models such as perfectly plastic linearly hardening or powerlaw-hardening materials. The obvious way of avoiding these difficulties is to consider spatial extension of the process region.

At an on going STUF-sponsored investigation the process region is modelled as a line shaped cohesive zone (see fig. 1). The physical properties of the model is given by a relation between the cohesive stress and the separation of the cohesive zone surfaces. The relationship might f. i. be given by a diagram such as the one in fig. 2. We note that the energy consumed in the cohesive zone is represented by the area below the curve $\sigma_y=\sigma_y(v)$ (see fig.1 for notations). The distribution of plastic strain in the remote parts of the plastic zone is fairly well understood through numerical studies. The amount of energy consumed in the process region is not known and further the relation between and surface energy is not known. Most of the plastic work is likely to leed to heat after a very short period of time, related to the lattice time period which normally is of the order 10^{-10} - 10^{-14}.

In order to observe emission of light from the crack tip neighbourhood a simple experiment was performed. Such emission has earlier been observed from cracks in quarts [1]. A three point bend specimen was slowly loaded. The load was applied so that sparks from friction at the loading device was avoided (see fig. 3). As the experiment was performed in "total" darkness a photomultiplicator registered very few photons before the test was started. As the load was applied emission of photons was registred during the slow crack growth. As much ass 20 to 100 times the background radiation was registred. The experiment was repeated several times with identical results.

In an attempt to explain the emission of photons a crack in a perfectly plastic material is studied.A mode III crack is studied for its mathematical simplicity.The process region is here assumed to be point shaped.

For the stationary mode III crack (see fig. 4) at small scale yielding, the plastic strain γ_p is given as follows:

$$\gamma_p = \frac{k_{III}^2}{\pi \tau_Y G} \frac{\cos\theta}{r} - \frac{\tau_Y}{G} \text{ for } \gamma_p > 0 \tag{1}$$

where τ_Y is the shear yield stress, G is the elastic modulus at shear and K_{III} is the stress intensity factor. The polar coordinate system r, θ is attached to the crack tip.

If we assume that a) all plastic work is transformed to thermal energy [2] and b) the load is applied sufficiently fast so that the process can be assumed to be adiabatic outside a distance r_0 from the crack tip. Then the temperature distribution T is easily calculated from the calorimetric formula

$$\frac{dW}{dm} = \frac{\tau_Y \gamma_p}{\rho} = cT \tag{2}$$

where dW/dm is the plastic work per unit of volume, ρ is the mass density and c is the heat capacity per unit of volume. One obtains the following

$$T = \frac{\tau_Y^2}{c\rho G} \left(\frac{2R_p}{r} \cos\theta - 1 \right) \text{ for } T > 0 \tag{3}$$

where $2R_p$ is the linear extension of the plastic zone straight ahead of the crack tip. R_p is given by

$$R_p = \frac{1}{2\pi} \left(\frac{K_{III}}{\tau_Y} \right)^2 \tag{4}$$

For a typical steel with c =460Ws/kgK, ρ =7800kg/m^3 and τ_Y=100MPa, the result is a surprisingly low temperature in the major part of the plastic zone, e.g. the temperature is 7 K at $r=10^{-2}R_p$ and 700 K at $r=10^{-4}R_p$ Note that it is assumed that $r<r_o$. In order to check the validity of the assumption of adiabatic processes for $r>r_o$ we use the governing equation for transient heat conductivity

$$\frac{\partial T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2} = \frac{c\rho}{\lambda}\frac{\partial T}{\partial t} \tag{5}$$

The relative temperature rate dT/(Tdt) is obtained as

$$\frac{dT}{Tdt} = -\frac{3\lambda}{c\rho r^2} \left(1 - \frac{r}{2R_p \cos\theta} \right)^{-1} \tag{6}$$

For an example we choose a rise time Δt for the remote load and assume, to simplify the calculations, small values for $r_o\cos\theta$. The following value for r_o is estimated

$$r_0 = \left[\frac{3\lambda T}{c\rho(dT/dt)} \right]^{\frac{1}{2}} \tag{7}$$

It seems reasonable to put the largest acceptable value for $dT/(Tdt)$ equal to $0.1/\Delta t$ for an adiabatic process. For a typical steel (λ=45W/mK) we obtain r_o=0.6mm. This result implies that a rather large region around the crack tip cannot be considered as adiabatic.

Instead we assume, rather roughly, that a region in which say $dT/(Tdt)>10^3/\Delta t$ (i.e. $r<r_o$ is isothermal. Then within the frame work of the model assumed the temperature for $r<r_o/100$ is given by the average over the area $r<r_o/100$ and $-\pi/4<\theta<\pi/4$ i.e.

$$T = \frac{400}{\pi} \frac{\tau_Y^2}{c\rho G} \frac{R_p}{r_0} . \tag{8}$$

With G=80GPa and R_p=5 mm the temperature equals 36 K (which of course should be understood as a temperature of 36K above an environmental temperature of say 20°C, i.e. T=56°C.

As regards the observed emission of photons 56°C is a very low temperature. The peak intensity would be for a photon energy of 0.2 eV. In the sensitive region for the standard photomultiplicator used, the total emitted photons are very few . Thus the distinct emission that actually was registered can hardly be explained by the temperature rise alone.

One explanation can be that the plastic straining involves processes responsible for the radiation. Another possibility is that such processes are located inside the process region, which was not considered in the analyses above. Even radiation after excitation by mechanically induced electrones might be possible (cf. [3]).

We believe that further research is urgently needed. We also believe that a study of the light spectra and intensity emitted from stationary and running cracks might provide information regarding the dependence of the fracture processes on conditions such as crack propagation rate and environmental factors. Further the possibilities of employing the effects for crack tip speed measuraments ought to be investigated.

Scope of the Project

A project is proposed that has the character of a pilot study. It is a pilot study in the sense that guide lines for application should be adviced and the possibility of developing of tools for crack tip measurements should be clear at the end of the project.

The project is assembled of the following two parts:

1) The emitted light spectra is investigated for a three point bend specimen under slow and rapid load conditions aswell as different scales of yielding and different environment temperatures in different materials.

The test specimen may have to be modified in order to avoid shear lips that might screen the emitted light (see fig 5). The light intensity is measured after diffraction with a few photomultiplicators. Several experiments have to be performed to give a complete spectra (see fig 3).

2)The average crack tip speed is measured with two photomultiplicators which are located at two different distances along the plane of the initial crack. It should be noted that the bandwidth of the photomultiplicator allows measurements on a time scale which is quite sufficient for measuring crack tip speeds in steel.

References

[1] R. Weichert and K. Schonert, J.Mech.Phys.Solids, vol.26,p.151,1978.

[2] G.I. Taylor and H. Quinney, Mech. of Solids (Edt. G.K. Batchelor) vol.1,p.310,1958.

[3] J. Walker, Scientific American, vol.247,p.124,1982.