Thermomechanical aspects of fatigue crack propagation

N. Ranc, N. Saintier, T. Palin-Luc and P.C. Paris*

Arts et Métiers ParisTech, PIMM, CNRS, Paris
Arts et Métiers ParisTech, I2M, CNRS, Bordeaux
*Washington Univ. St Louis, USA, Visiting professor at Arts et Métiers ParisTech

Photomechanics 2013, 27 - 29 May, Montpellier, France

Introduction

For a cracked structure under cyclic loading (fatigue loading) the driving force for crack propagation is the **stress intensity factor** $K(t)$

Usually :

- The temperature of a cracked structure during a cyclic loading is supposed to be **homogeneous and constant**
- At room temperature, **no effect of temperature is considered** on $K(t)$ and on crack propagation

But several studies in the literature show that the temperature field at a crack tip is heterogeneous and not negligible

Objectives of this work

During fatigue crack propagation there are :

- Alternating plasticity near the crack tip
- **Dissipation of the plastic energy in heat**
- **Heterogeneous temperature field** around the crack tip due to dissipation
- **A thermal stress field** associated to the thermal expansion [a]

This changes the stress state around the crack tip !

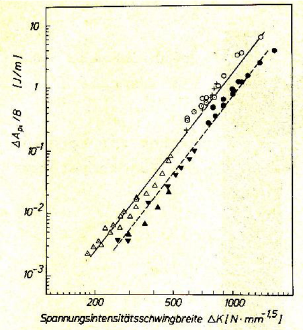
a. Ranc, Palin-Luc, Paris (2011) Engng. Fract. Mech., vol.78 961-972

Aim of this work : quantify this thermal effect (due to dissipation in heat) on the stress intensity factor

Results in the literature about the plastic work during cyclic loading

In literature plastic work per cycle and thickness was deduced from temperature or mechanical measurments and analytical and numerical simulations :

- in 1964, P.C. Paris (P.C. Paris, "fatigue - the fracture mechanics apporach", Fatigue an interdisciplinary approach, *Syracuse University Press*, 1964)
- in 1967, J.R. Rice (J.R. Rice, "mechanics of crack tip deformation and extension", Fatigue Crack Propagation, ASTM STP415, 1967, 247-311)
- in 1983, R. Pippan and H.P. Stüwe (R. Pippan and H.P. Stüwe, 1983, Z. Metalkunde, Vol. 74, pp. 699-704)
- in 2003, N.W. Klingbeil (N.W. Klingbeil, 2003, Int. J. Fatigue, 25 (2003)117-128)



Plastic work per cycle and per unit length of crack according to the stress itensity factor(from Pippan and Stüwe, 1983)

The results show that the plastic work per cycle is

- proportional to ΔK^4
- independent of the R ratio
- independent of the loading frequency
- dependent of the material

However there is no study on the thermal effect on the stress intensity factor

Theorical aspects on the plasticity near the crack tip during a cyclic loading

Theorical aspects on the plasticity near the crack tip during a cyclic loading

Theorical aspects on the plasticity near the crack tip during a cyclic loading

- During a cyclic loading of a fatigue crack, the plasticity is located in **the reverse cyclic plastic zone**(RCPZ)
- In plane stress, the reverse cyclic plastic zone radius is equal to :

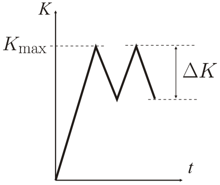
$$r_R = \frac{\Delta K^2}{8\pi\sigma_y^2} \qquad \left(r_y = \frac{K_{max}^2}{2\pi\sigma_y^2} \right)$$

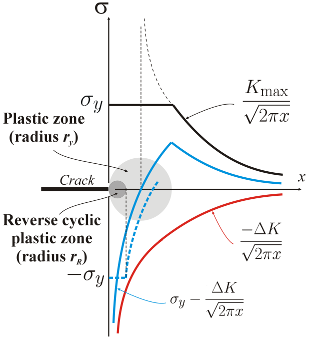
  where ΔK is the variation of the stress intensity factor and σ_y the yield stress.

- The dissipated power per unit length of crack front is assumed to be proportional to :
  - **The surface area of the reverse cyclic plastic zone**
  - **The loading frequency**

$$q = f\mathcal{E} = f\eta r_R^2$$

- Example : In plane stress $q = f\mathcal{E} = f\eta \frac{\Delta K^4}{64\pi^2\sigma_y^4} = q_0 \Delta K^4$



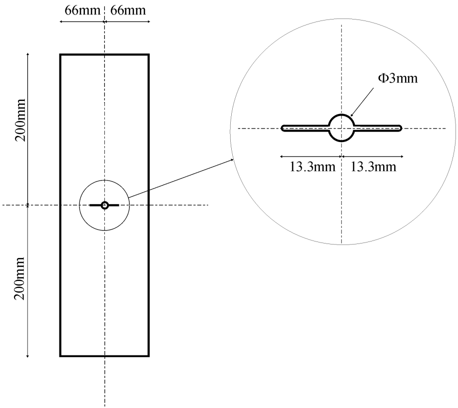


Determination of the dissipated power per unit length of crack

Determination of the dissipated power per unit length of crack

Experimental device

Crack propagation test on vibrophore is carried out



Cracked specimen geometry

Experimental conditions

- Pre-cracked specimen
- Specimen thickness $t = 4\ mm$
- Material : C40 steel (yield stress 315 MPa)
- Mat black paint surface for the temperature measurements

Temperature field measurements with infrared CCD camera

- Spectral range $3.9\,\mu m - 4.5\,\mu m$
- NEDT=20 mK
- Aquisition frequency : 5 Hz
- Aperture time : 1500 μs

Experimental conditions

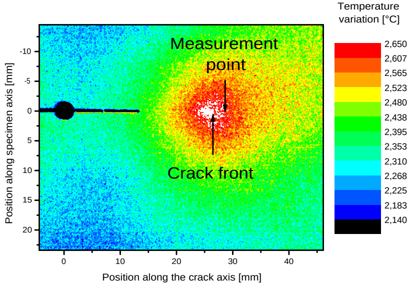
Fatigue test on cracked plate specimen are carried out with a vibrophore

- Precracking : $R = 0.1$ at $200Hz$, $\Delta K = 17\ MPa\sqrt{m}$
- Loading frequency : 200 Hz
- R ratio : 0.1
- Test conditions

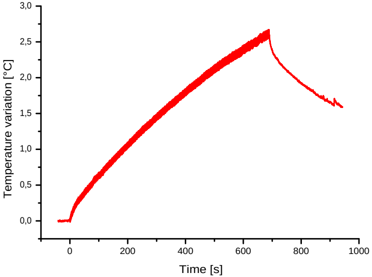
Ref	initial length in mm	final length in mm	initial stress intensity factor ΔK in $MPa\sqrt{m}$	cycle number	Testing time in s	Mean crack growth rate $m/cycle$	$\mu m/s$
1	21.9	26.3	20	137800	689	22×10^{-6}	6.4

Experimental results

Temperature field near the crack tip



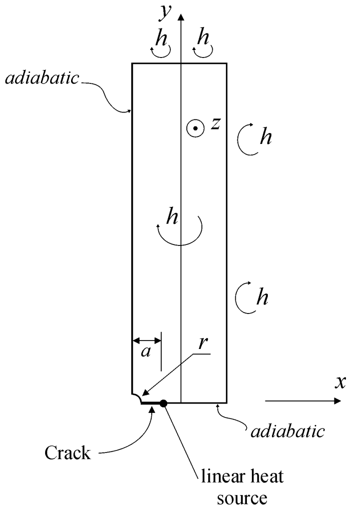
Temperature evolution in the measurement point



Temperature evolution results

- Heterogeneous temperature field
- Oscillations : thermo-elastic effect
- Mean temperature variation for 20 $MPa\sqrt{m}$: $2.5^{\circ}C$

Geometry and boundary conditions of the thermal problem



Geometry of the problem

- Plane problem
- Dissipated power : 1 Wm^{-1}
- Homogeneous initial temperature equal to the ambient : at $t = 0$, $\vartheta(r,t) = T(r,t) - T_0 = 0$
- Stationary regime :

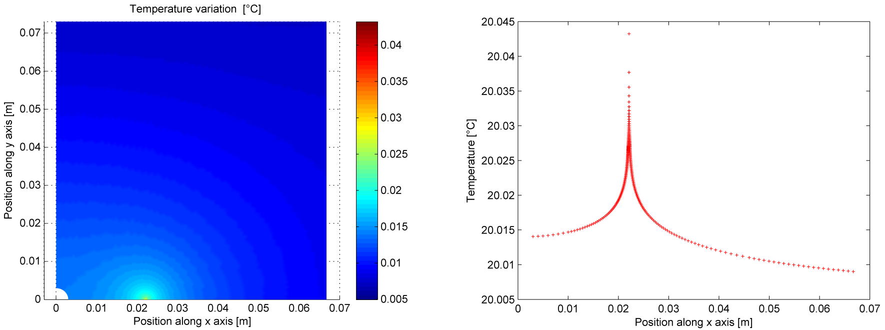
$$q\delta(x-a)\delta(y) + \lambda\left(\frac{\partial^2\vartheta}{\partial x^2} + \frac{\partial^2\vartheta}{\partial y^2}\right) = 0$$

with λ the heat conductivity and δ the Dirac function.

Boundary conditions

- Convection on the specimen surfaces ($h = 10\ Wm^{-2}K^{-1}$)
- Convection on the free edges of the specimen ($h = 10\ Wm^{-2}K^{-1}$)
- Adiabatic on the symmetry axis

Results of the thermal problem



- Computation for $q = 1\ W.m^{-1}$ in front of the crack tip (zone 2) gives : $T - T_0 = 0.0163^\circ C$
- From IR measurement in the same zone : $T - T_0 = 2.5^\circ C$
- The thermal problem is linear (i.e. temperature variation is proportional to the heat flux)
- $\Longrightarrow$ **Heat flux identified :** $q = 158 W.m^{-1}$

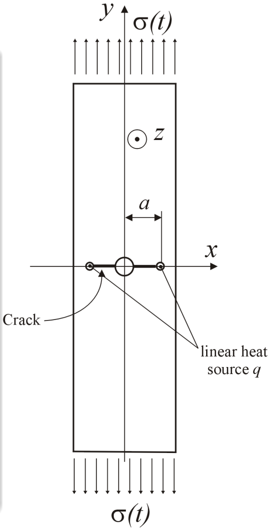
Calculation of the stress field

Calculation of the stress field

The thermomechanical problem

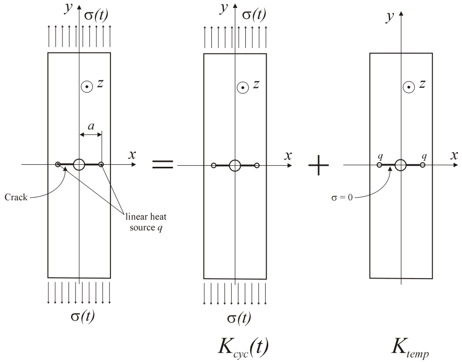
Assumptions of the thermomechanical problem

- The reverse cyclic plastic zone is small and a line heat source is considered,
- Slow moving crack ; static and constant heat source during the test,
- The stress is calculate using the temperature field obtained previously,
- Plane stress conditions,
- Outside the RCPZ, the material behavior is suppose to be thermo-elastic : $E = 210\ GPa$, $\nu = 0.29$, $\rho = 7800\ kgm^{-3}$ and $\alpha = 1.2 \times 10^{-5}\ K^{-1}$,
- Because of the alternating plasticity in the RCPZ, the mean radial stress tends toward to zero at the interface with the RCPZ,
- because K_I is computed from the stress field outside the RCPZ, only the elastic domain is considered.



Decomposition of the thermomechanical problem

Decomposition in a purely mechanical problem and a purely thermal problem

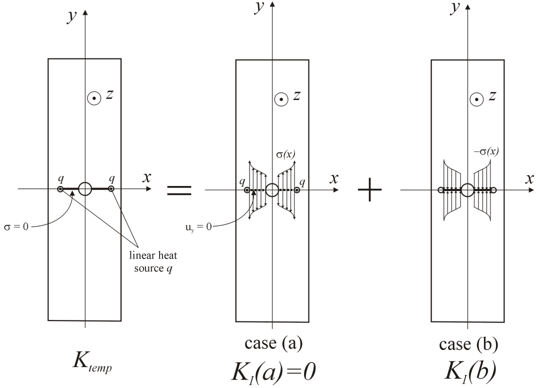


This decomposition is correct if :

- the heating effects are small and do not modify the size of the RCPZ
- the compressive stress does not create crack closure

Decomposition of the purely thermal problem

Decomposition of the purely thermal problem in two cases

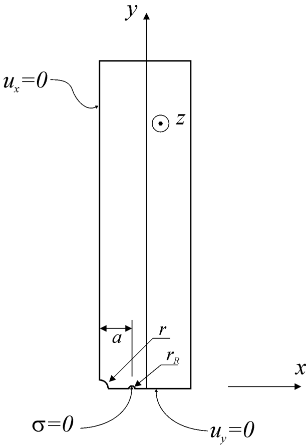


- The case (a) without crack allows to calculate the stress distribution $\sigma(x)$
- The case (b) with crack allows to calculate the stress intensity factor K_{temp} via the Green function

Resolution of the case (a), determination of $\sigma(x)$

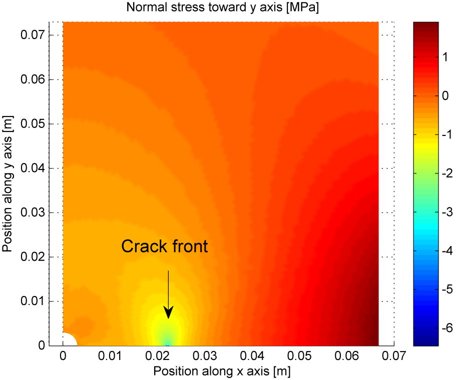
Geometry and boundary conditions of the case(a) problem

- Temperature field associated to a dissipated power of 158 Wm^{-1},
- Thermoelastic behavior,
- without crack :$u_y = 0$ on the x axis,
- symmetry boundary conditions on the left edge
- alternating plasticity : no normal stress on the RCPZ interface

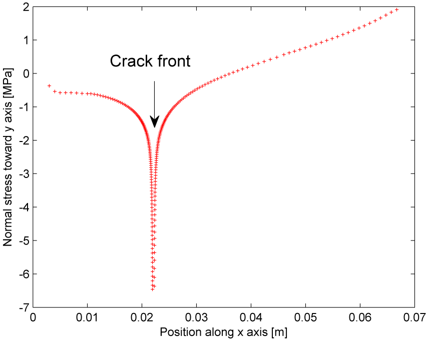


Results : evolution of the normal stress toward y axis

Normal stress toward y axis distribution



Normal stress toward y axis along x axis



Negative stress (compression) in a zone close to the crack tip

Calculation of the associated stress intesity factor

Calculation of the associated stress intesity factor

Calculation of the effect on the stress intensity factor

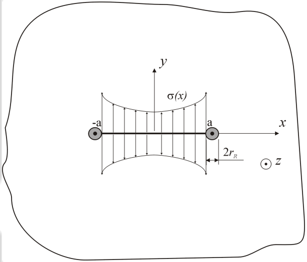
Calculation of the effect on the stress intensity factor

The effect on the stress intensity factor is calculated with equation :

$$K_{temp} = \frac{2}{\sqrt{\pi}} \int_0^a \sigma(x) \frac{\sqrt{a}}{\sqrt{a^2 - x^2}} \mathrm{d}x$$

For a dissipated power of 158 Wm^{-1} ($\Delta K = 20\ MPa\sqrt{m}$ and $R = 0.1$), $K_{temp} = -0.3\ MPa\sqrt{m}$

- Negative value due to the compressive stress state near the crack tip
- Small thermal effects for these test condition (C40 steel, $\Delta K = 20\ MPa\sqrt{m}$ and a loading frequency of 200 Hz)



Discussion and conclusion

Discussion and conclusion

Discussion and conclusion

- Due to the dissipation in heat in the RCPZ there are thermal stresses ahead of the crack tip
- They modify the stress intensity factor during a fatigue loading, it has to be corrected by the negative factor K_{temp} :

$$K_I(t) = K_{cyc}(t) + K_{temp}$$

- The temperature has no effect on ΔK but it has an effect on K_{max} and K_{min} :

$$K_{max} = K_{cyc\ max} + K_{temp} \quad \text{and} \quad K_{min} = K_{cyc\ min} + K_{temp}$$

- The ratio $R_K = \frac{K_{min}}{K_{max}}$ is affected by the temperature correction :

$$R_K = \frac{K_{cyc\ min} + K_{temp}}{K_{cyc\ max} + K_{temp}} \neq \frac{K_{cyc\ min}}{K_{cyc\ max}}$$

- for a stress intensity factor $\Delta K = 20\ MPa\sqrt{m}$ and a $R_K = 0.1$, the thermal correction gives $R_K = 0.11$ (10%)

- The thermal correction in our experimental conditions remains small,
- Is this thermal effect always negligible, and especially in the case of materials with lower yield stress or for tests carried out with higher frequency ?

Thank you for your attention