12th International Conference on Fracture

Study of crack propagation by infrared thermography during very high cycle fatigue regime

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Introduction

- Many elements of mechanical structures can be loaded beyond 10^7 cycles :

$\Rightarrow$ Very high cycle fatigue regime (VHCF) or gigacycle fatigue regime

- Fracture mechanisms associated with the VHCF are different from those known in high cycle fatigue (HCF) :
  - **Fatigue failure can occur at values of cycle exceed 10^7 cycles and for stress level below the conventional high cycle fatigue limit.**
  - **In high yield strength steels the fracture does not occur on the surface but rather internally in the materials : formation of a fish eye**

Experimental study of the crack propagation in the VHCF regime

- Experimental difficulties :
  - High frequency : In gigacycle fatigue test is carried out at ultrasonic frequency (20kHz) one cycle : 50µs
  - Test duration : 14 hours for 10^9 cycles
  - Internal crack initiation

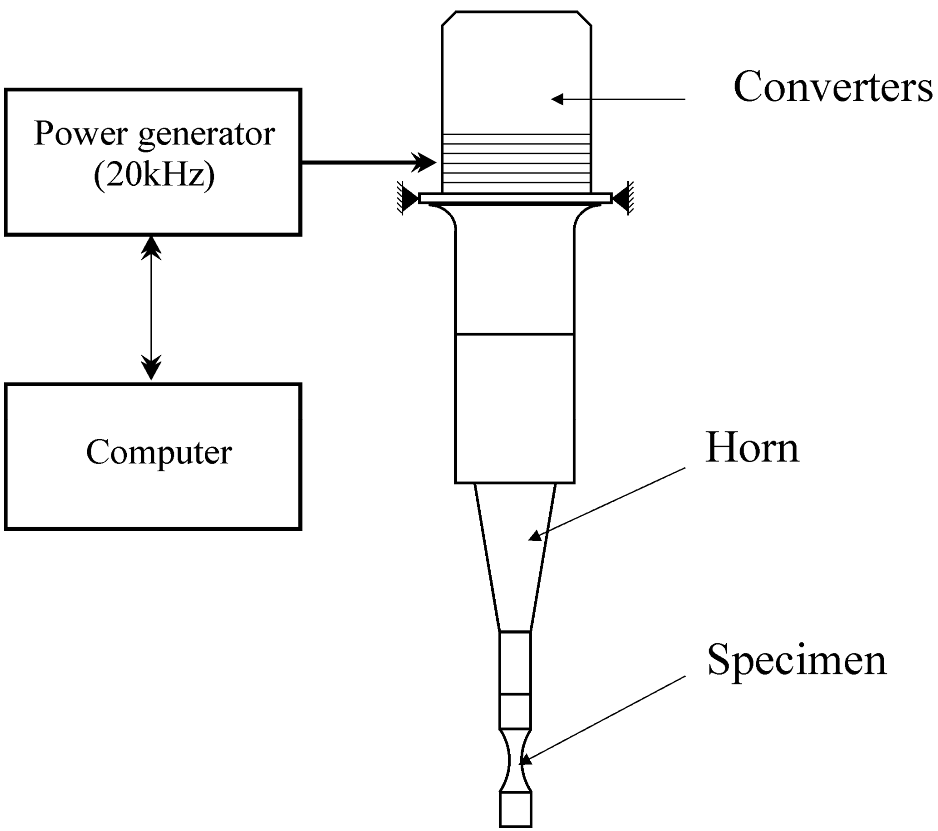
⇨ Is it possible to use pyrometry to understand and to study the fatigue initiation in VHCF regime?

- Advantage of pyrometry technique:
  - Good spatial and time resolutions
  - It allows to obtain field measurements on the surface of the specimen
  - The dissipated power is higher than at low frequency
  - It allows to detect the thermal effects associated with an internal crack propagation (the fish eye formation, i.e. crack propagation , inside the material in the gigacycle fatigue regime is related to a local increase of the temperature due to plasticity on the crack tip.)

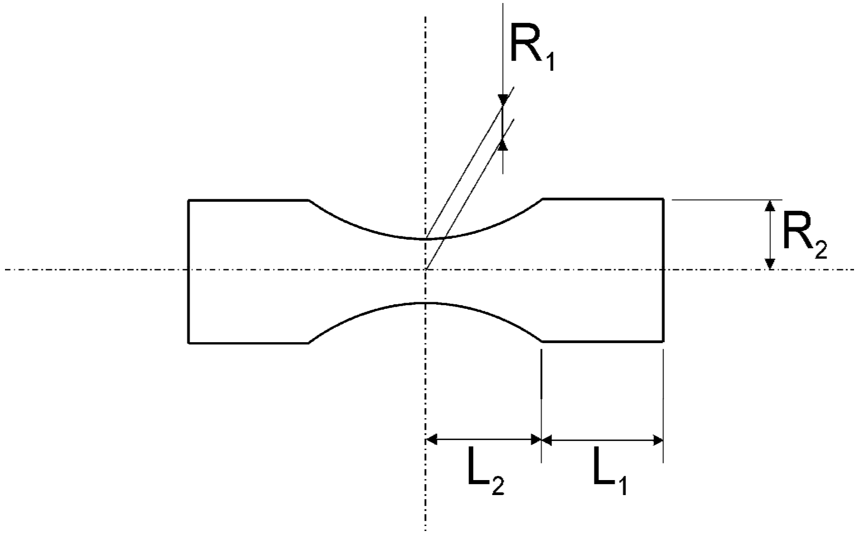
Experimental device : ultrasonic fatigue test with measurement of temperature fields

Experimental device : ultrasonic fatigue test

- Ultrasonic fatigue machine



- Geometry of the specimen



R_1=1.5mm
R_2=10mm
L_1=16mm
L_2=10mm

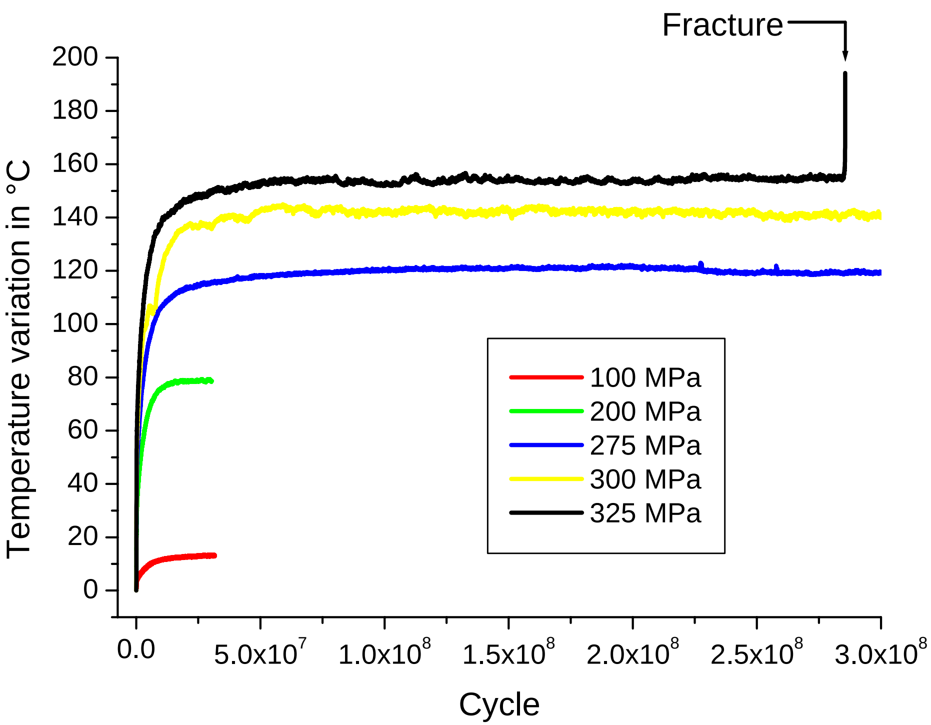
Experimental device : temperature field measurement

Experimental device : test with R=0.01

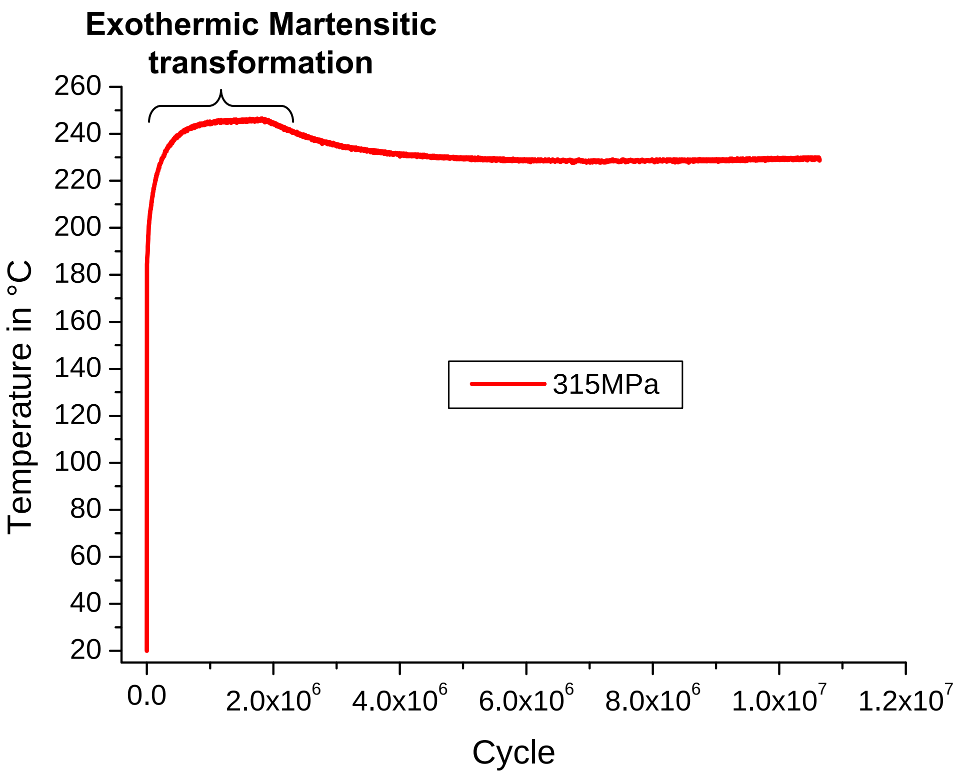
- **Temperature measurement by infrared pyrometry:**
  - **MCT detector**
  - **Wavelength range : 3.7µm – 4.9µm**
  - **Aperture time : 100µs-1500µs**
  - **Refresh time : 16ms – 40ms**
  - **Spatial resolution : 0.12mm/pixel**

Temperature evolution during an ultrasonic fatigue test

- **Case of a high-strength steel : (0.22% of C; 1.22% of Mn; 1% of Cr; 1% of Ni); UTS = 950MPa**



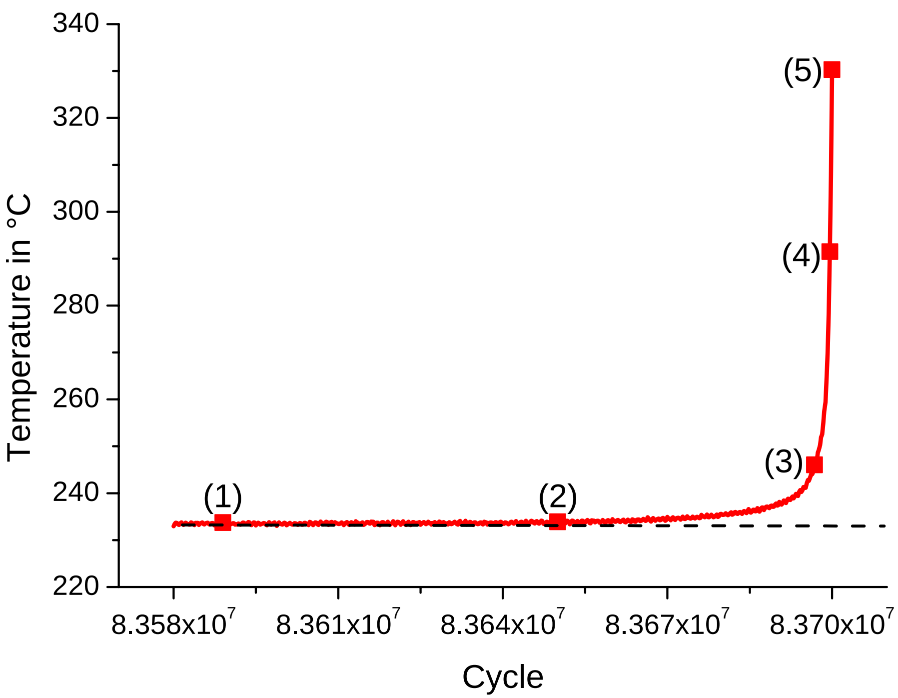
- **Case of another high-strength steel : (0.22% of C; Mn, Cr, Si: less than 1%); UTS ≈ 1700MPa**



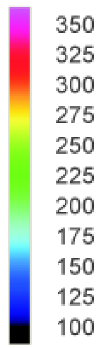
Specimen is cooled by an air circulation in order to limit its heating

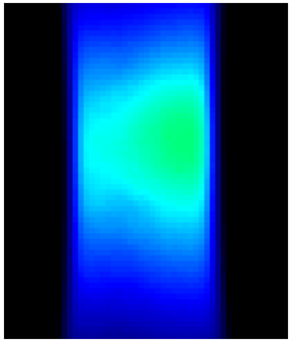
Temperature field just before the fracture

- **R=-1; $\Delta\sigma$=335MPa; N_F=8.37x10^7 cycles (gigacycle domain)**



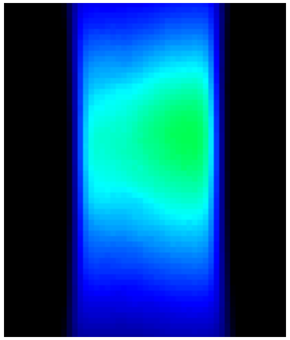
Temperature in °C





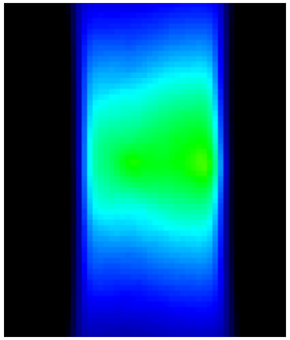
(1)

N = 8.35890x10^7 cycles



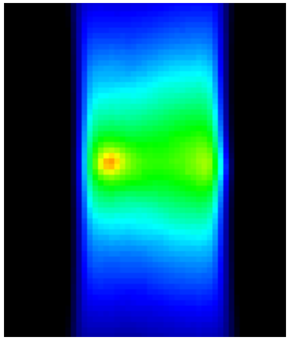
(2)

N = 8.36500x10^7 cycles



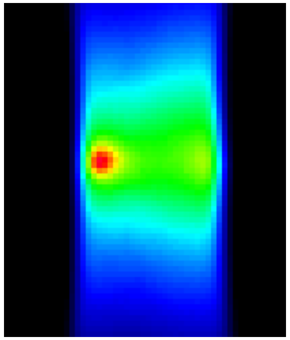
(3)

N = 8.36968x10^7 cycles



(4)

N = 8.36996x10^7 cycles



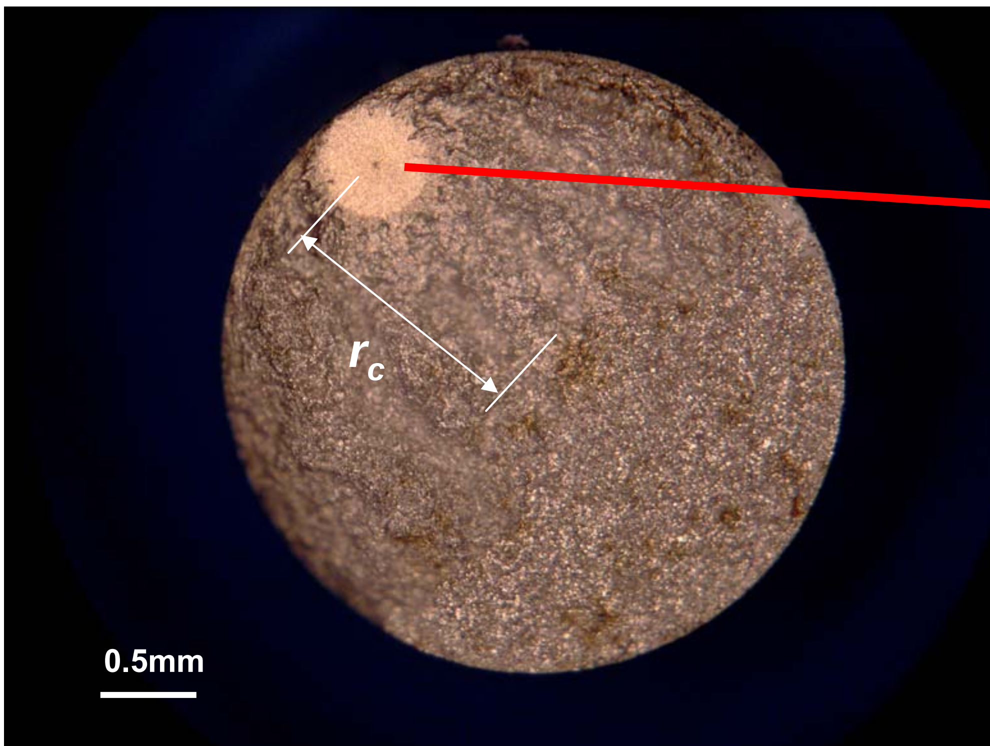
(5)

N = 8.37000x10^7 cycles

Post mortem observation of the fracture surface

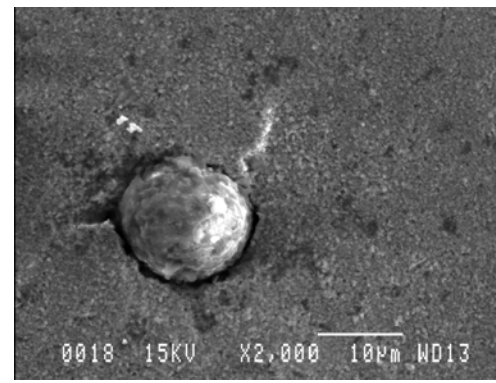
- Optical microscopy

Observation direction



Propagation of a fish eye fatigue crack

- Scanning electronic microscopy



Inclusion in the center of the fatigue crack :

⇒**Average radius of the inclusion: a_{int}=7.6µm**

⇒**Eccentricity: $e=r_c/R_1=0.81$**

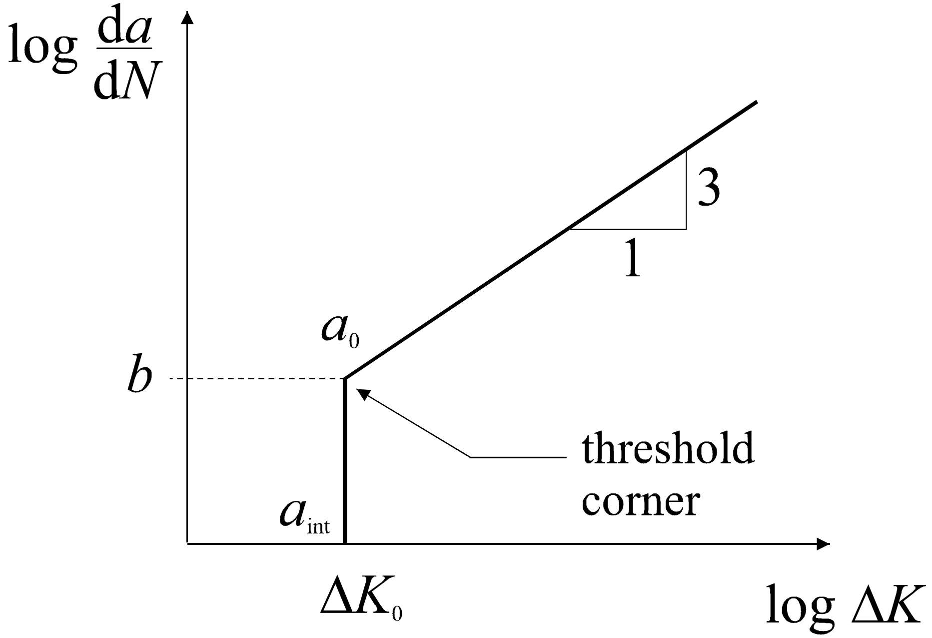
Thermal model of the crack propagation

The model of crack propagation 1

- **Paris-Hertzberg-McClintock crack growth rate law :**

$$\frac{\mathrm{d}a}{\mathrm{d}N} = b\left(\frac{\Delta K_{eff}}{E\sqrt{b}}\right)^3$$

b norm of the Bürgers vector
E Young modulus



- **On the threshold corner**

$$\frac{\mathrm{d}a}{\mathrm{d}N} = b \quad \text{and} \quad \frac{\Delta K_0}{E\sqrt{b}} = 1$$

The model of crack propagation 2

By supposing a circular crack and neglecting crack closure:

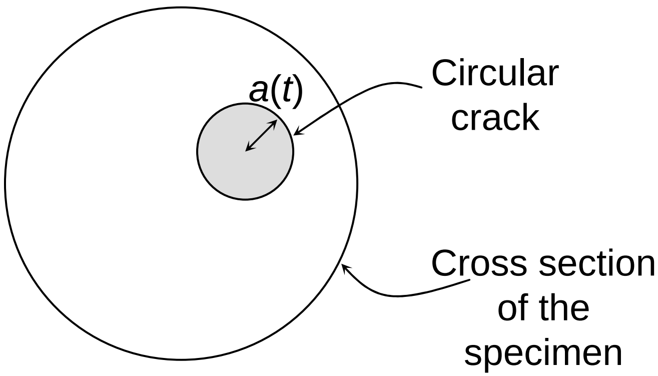
$$\Delta K_{eff} = \Delta K = \frac{2}{\pi}\Delta\sigma\sqrt{\pi a}$$

The crack growth rate law is thus written:

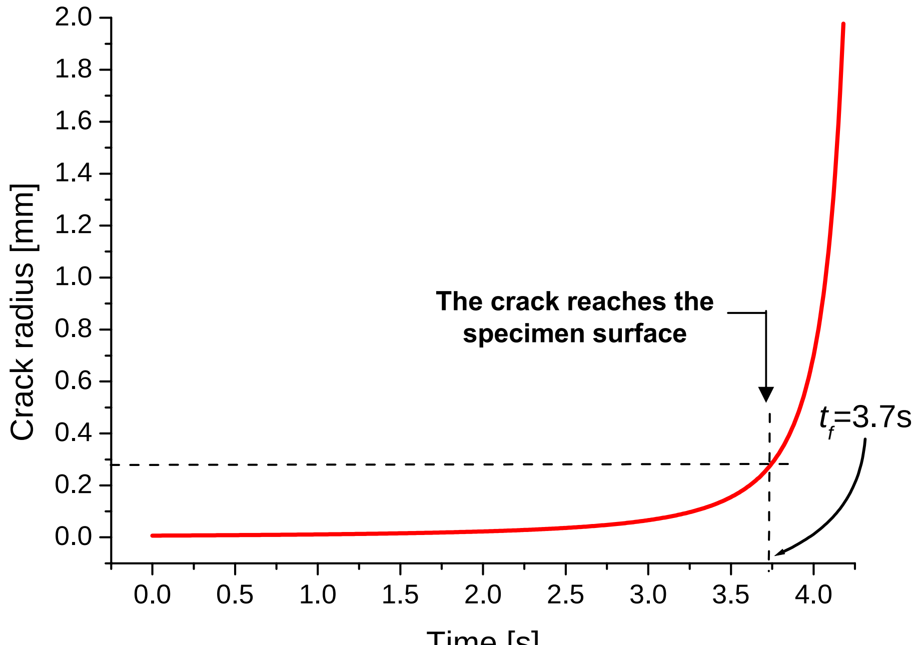
$$\frac{\mathrm{d}a}{\mathrm{d}N} = b\left(\frac{\Delta K}{\Delta K_0}\right)^3 = b\left(\frac{a}{a_0}\right)^{3/2}$$

After integration between a_0 (t=0) and a (time t):

$$a(t) = \frac{a_0}{\left(1-\frac{t}{t_c}\right)^2} \quad \text{with} \quad t_c = \frac{2a_0}{bf}$$



Geometry of the circular crack



Evolution of the crack radius
(a_0=8µm; e=0.8; t_c=4.4s)

Calculation of the dissipated energy during crack growth

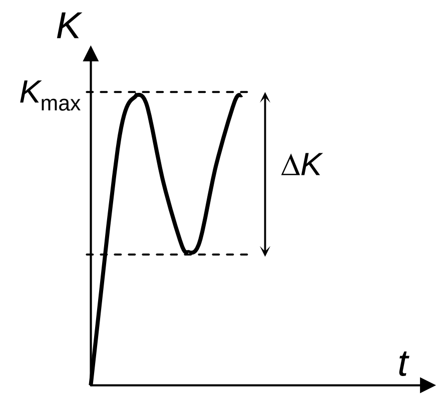
- **The reverse plastic zone size in plane strain:**

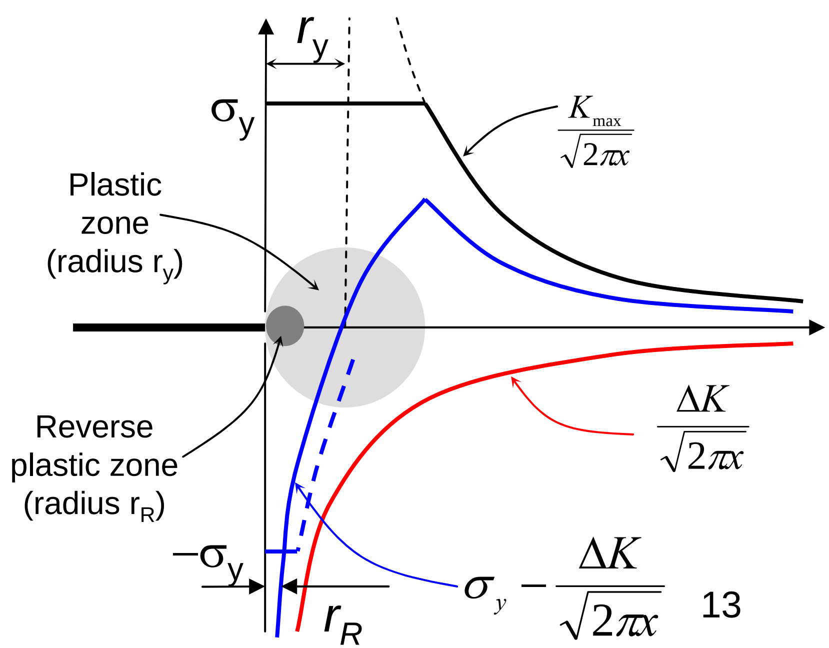
$$r_R = \frac{r_y}{4} = \frac{1}{6\pi}\frac{\Delta K^2}{(2\sigma_y)^2}$$

r_R**<0.13μm**

- **Energy dissipated per unit length of crack:**

$$E = \eta r_R^2$$





Calculation of the dissipated energy during crack growth

Evolution of the dissipated energy versus time:

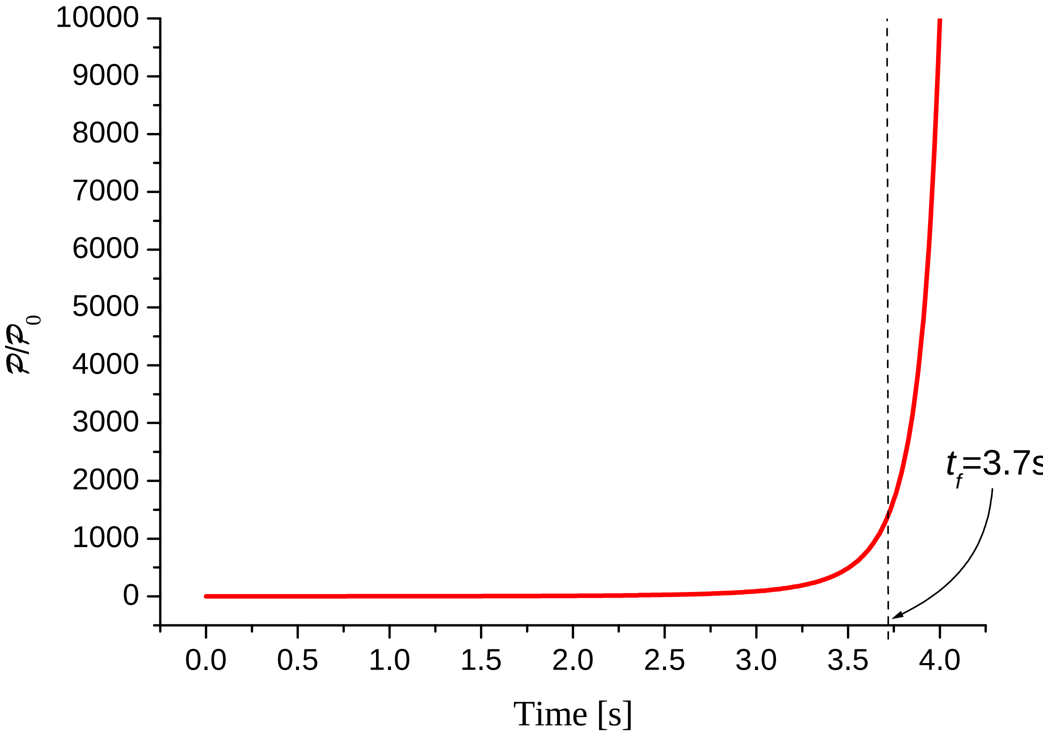
$$E = \eta r_R^2 = \eta \frac{\Delta K^4}{24^2 \pi^2 \sigma_y^4}$$

$$E = \eta \frac{a^2}{36\pi^4 \sigma_y^4} = \eta \frac{a_0^2 \Delta\sigma^4}{36\pi^4 \sigma_y^4 \left(1 - \frac{t}{t_c}\right)^4}$$

Evolution of the dissipated power versus time:

$$P = Ef = \frac{P_0}{\left(1 - \frac{t}{t_c}\right)^4} \quad \text{with} \quad t_c = \frac{2a_0}{bf}$$

***P_0* is a constant which is identified from experimental data**



Evolution of dissipated power (a_0=8μm; *e*=0.8; t_c=4.4s)

Modeling of the thermal problem

- Thermal model assumptions:
  - The specimen is modeled by a cylinder with a radius of R_1=1.5mm
  - For symmetry reasons, only one half of the specimen is consider
  - r_R is very small (about 0.13µm) : the fatigue crack is modeled by a dissipated power along the crack tip (*P* is the dissipated power per unit length)

Heat transfer equation

- Heat transfer equation:

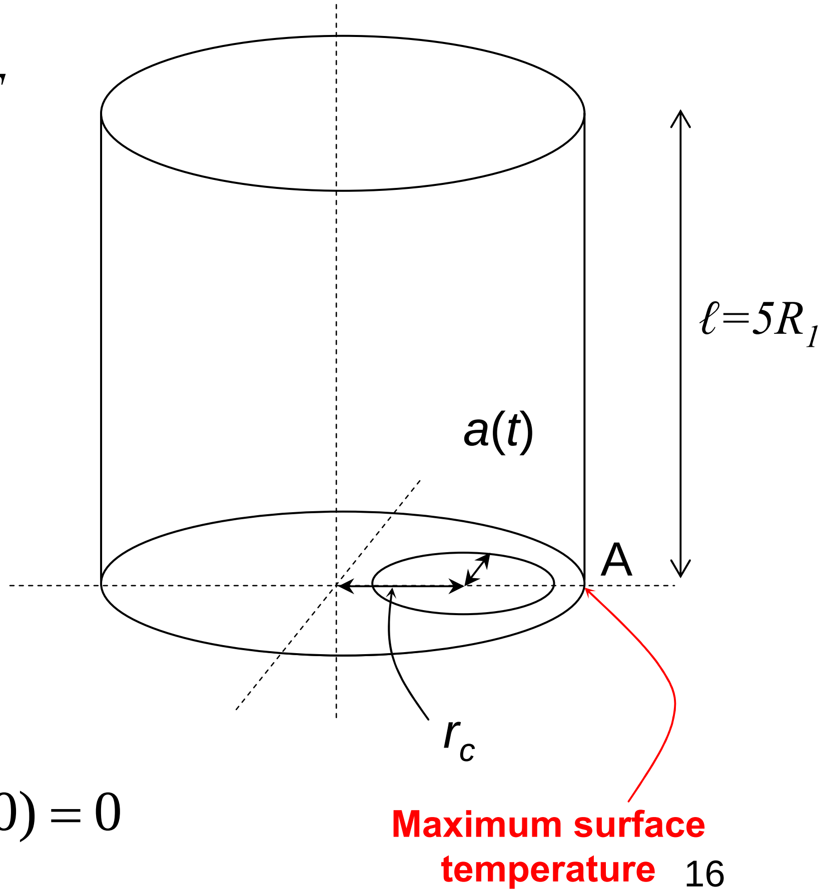
$$\rho C \frac{\partial T}{\partial t} = \frac{P(t)}{2} \delta(r_c - a(t)) \delta(z) + \lambda \Delta T$$

- Initial condition

$$T(t=0) = T_0$$

- Boundary condition (adiabatic conditions)

$$\frac{\partial T}{\partial r}(r = R_1) = 0 \quad \frac{\partial T}{\partial z}(z = \ell) = 0 \quad \frac{\partial T}{\partial z}(z = 0) = 0$$



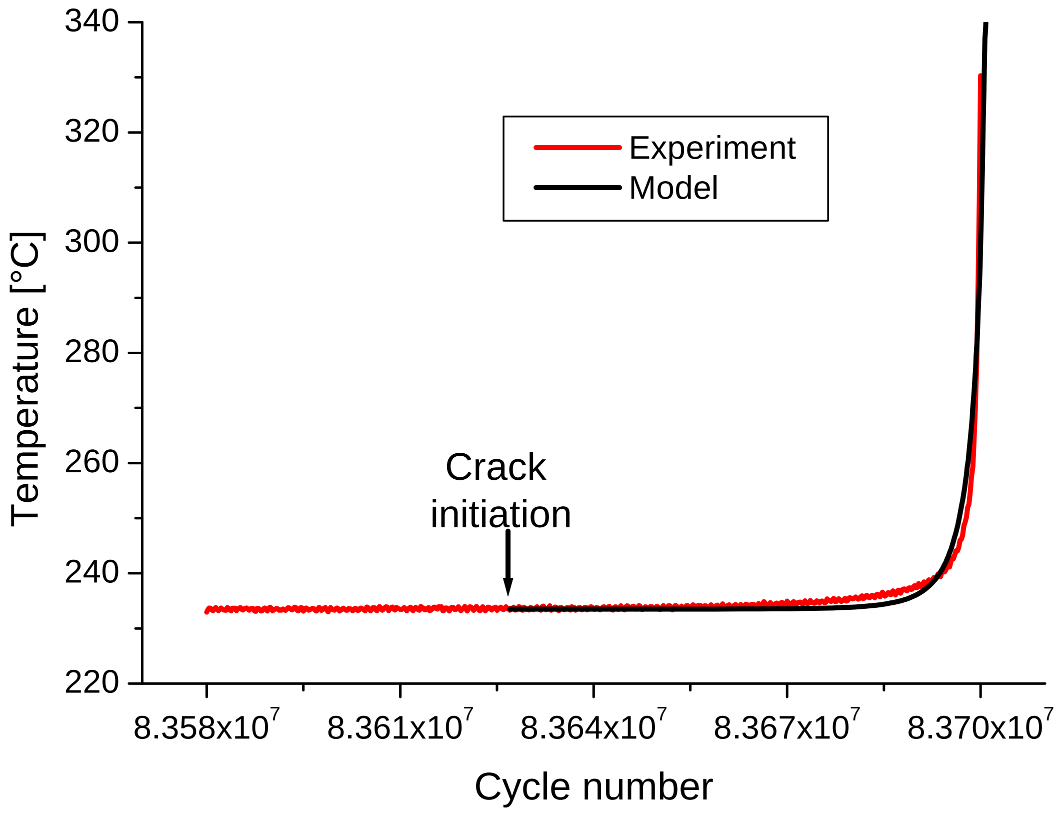
Numerical simulation of the temperature field 1

- The thermal problem is solve numerically with a finite element method:
  - Linear finite element
  - The integration scheme is implicit
  - The mesh is more refined in the zone close to the plan of crack propagation : 100 elements on the specimen radius
- Parameters of the simulation:
  - Initial crack radius: a_0=8µm
  - Eccentricity: e=0.8
  - Characteristic time: t_c=4.4s

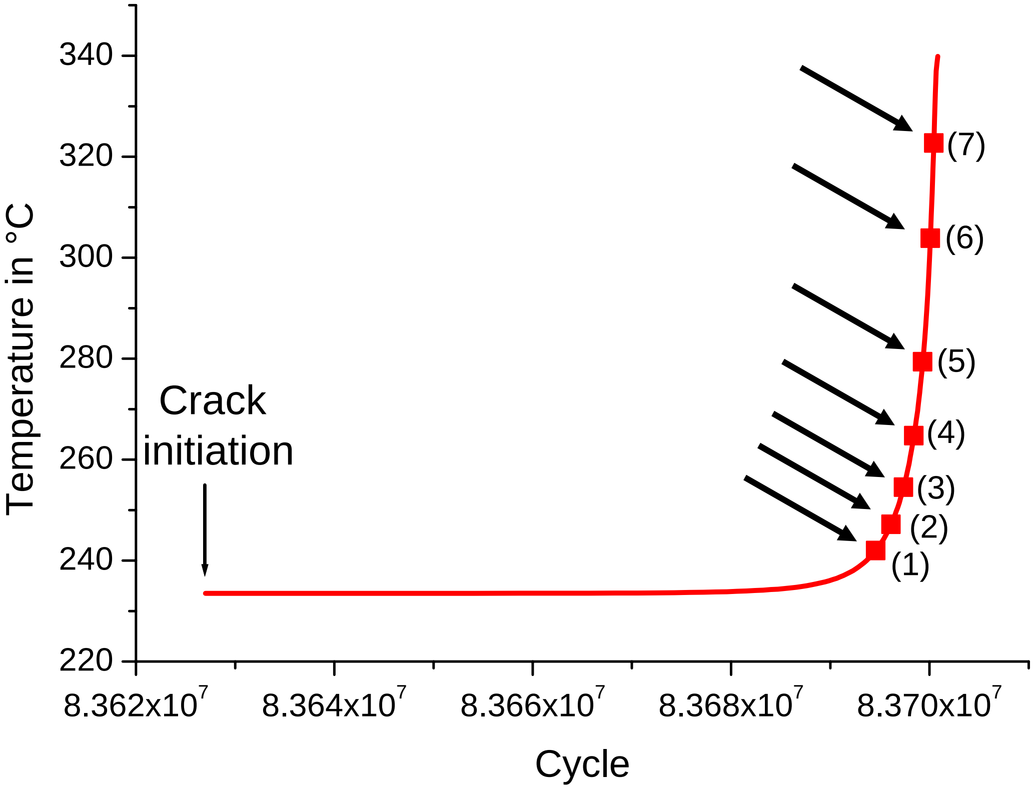
Identification of the dissipated power P_0

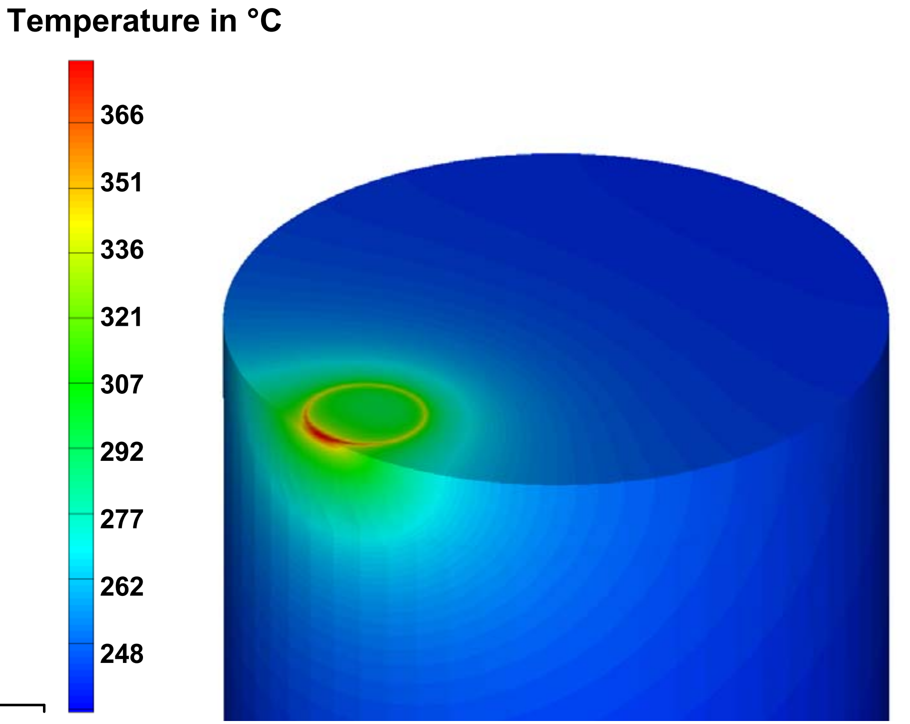
- **Minimization of least squares method :**

Minimization of least squares of the difference between the maximum temperature measured in experiments and the calculated temperature:
P_0=2.9Wm^{-1}



Numerical simulation associated to the experimental configuration





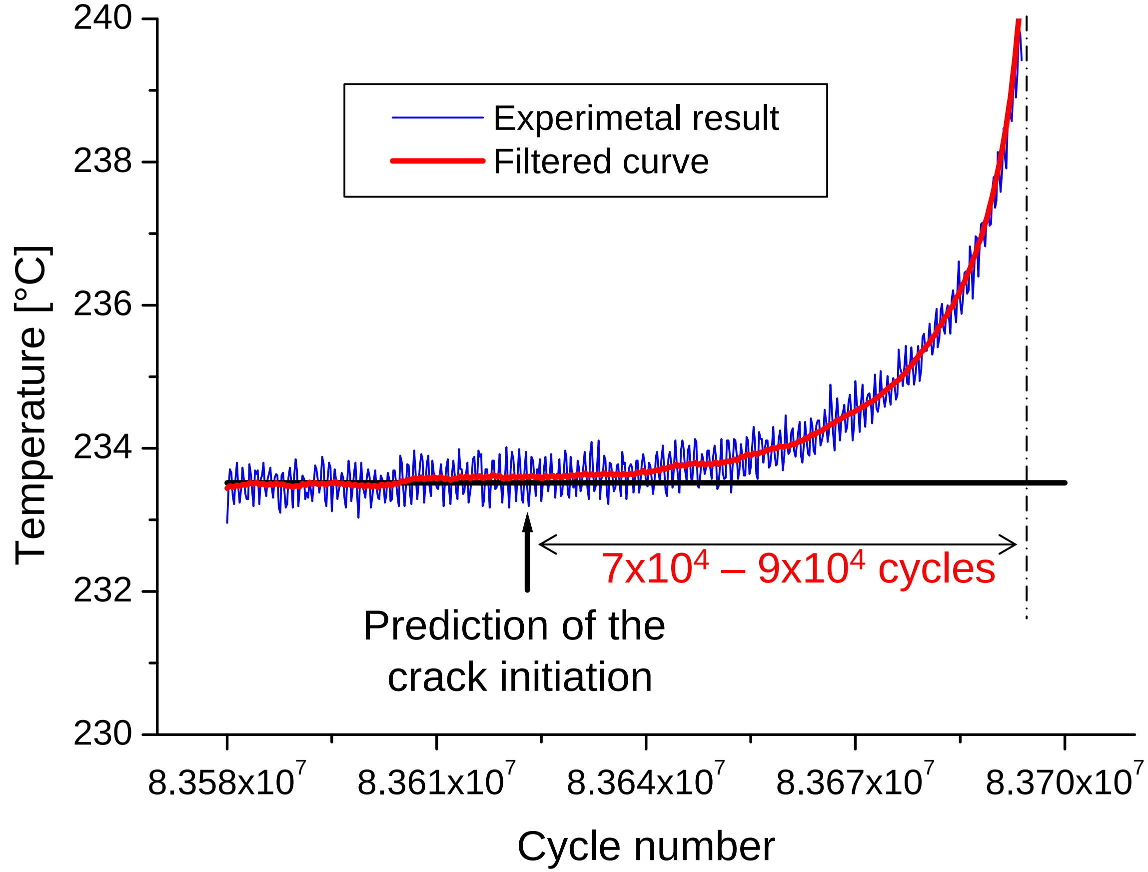
(7) N = 73594 cycles;
t = 3.68s; *a* = 0.270mm

Experimental determination of the crack initiation

- **Experimental crack initiation criterion: increase of 0.07∘C of the filtered temperature (a≈0.02mm)**

- **Crack propagation: between $7x10^4$ and $9x10^4$ cycles**

⇒ very small part of the life of the specimen



Conclusion

- Experimental approach : temperature measurement during ultrasonic fatigue test
- Modeling of the thermal effect associated to the crack propagation :
  - Crack propagation
  - Dissipated power during crack growth
  - Modeling of the thermal problem and numerical solution
- Results
  - Good correlation with the experiment
  - Good estimation of the crack propagation duration