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:

⇒ 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

Power generator (20kHz) -> Converters -> Computer

Horn -> Specimen

R₁=1.5mm
R₂=10mm
L₁=16mm
L₂=10mm
Experimental device: temperature field measurement

- 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

Experimental device: test with R=0.01
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

Exothermic Martensitic transformation

Specimen is cooled by an air circulation in order to limit its heating.
Temperature field just before the fracture

- $R=-1$; $\Delta \sigma=335\text{MPa}$; $N_F=8.37\times10^7$ cycles (gigacycle domain)
Post mortem observation of the fracture surface

- Optical microscopy

Observation direction

- Scanning electronic microscopy

Inclusion in the center of the fatigue crack:

- Average radius of the inclusion: $a_{int}=7.6\mu m$
- Eccentricity: $e=r_c/R_1=0.81$

Propagation of a fish eye fatigue crack
Thermal model of the crack propagation
The model of crack propagation

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

\[
\frac{da}{dN} = b \left( \frac{\Delta K_{\text{eff}}}{E \sqrt{b}} \right)^3
\]

- **On the threshold corner**

\[
\frac{da}{dN} = b \quad \text{and} \quad \frac{\Delta K_0}{E \sqrt{b}} = 1
\]

Where:
- \( b \): norm of the Bürgers vector
- \( E \): Young modulus
The model of crack propagation 2

By supposing a circular crack and neglecting crack closure:

\[ \Delta K_{\text{eff}} = \Delta K = \frac{2}{\pi} \Delta \sigma \sqrt{\pi a} \]

The crack growth rate law is thus written:

\[ \frac{da}{dN} = b \left( \frac{\Delta K}{\Delta K_0} \right)^3 = b \left( \frac{a}{a_0} \right)^{3/2} \]

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

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

With \( a_0 = 8 \mu m; \ e = 0.8; \ t_c = 4.4 s \)

\[ t_f = 3.7 s \]
Calculation of the dissipated energy during crack growth

- The reverse plastic zone size in plane strain:

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

\[ r_R < 0.13 \mu m \]

- 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:

\[ E = \eta \frac{\Delta K^4}{24^2 \pi^2 \sigma_y^4} \]

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

Evolution of the dissipated power versus time:

\[ P = E f = \frac{P_0}{\left(1 - \frac{t}{t_c}\right)^4} \quad \text{with} \quad t_c = \frac{2a_0}{bf} \]

\[ P_0 \text{ is a constant which is identified from experimental data} \]
Modeling of the thermal problem

- Thermal model assumptions:
  - The specimen is modeled by a cylinder with a radius of $R_1=1.5\text{mm}$
  - For symmetry reasons, only one half of the specimen is considered
  - $r_R$ 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

- The thermal problem is solved 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: $a_0 = 8\mu$m
  - 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:

$P_0 = 2.9 \text{Wm}^{-1}$
Numerical simulation associated to the experimental configuration

Temperature in °C

Crack initiation

Cycle

(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 ($a \approx 0.02\text{mm}$)

- Crack propagation: between $7 \times 10^4$ and $9 \times 10^4$ 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