Support of dissipated energy measurements for the fatigue design of short fibers composites and elastomers
et al.

Vincent LE SAUX, Sylvain CALLOCH, Cédric DOUDARD,
Bertrand HUNEAU, Habibou MAITOURNAM, Pierre CHARRIER, Ida RAOUlt, Gilles ROBERT,
Antoine LAUNAY, Loïc JEGOU, Isaure MASQUELIER, Leonell SERRANO, Clément CHAMPY,
Louis LEVEUF, Thomas GLANOWSKI,

...
Introduction: Industrial and scientific contexts

DURABILITY: FATIGUE and AGEING

Elastomeric materials

Short Fibres reinforced plastics and continuous fibers composites
Introduction: Industrial context for elastomers

- Compounding and Process
- Environment
- Thermomechanical loading
- Local defects
- Process and ageing gradients
- Population of damage sites
- Damage mechanisms
- Filler network mechanisms

Colloque National d’Aussois, Mécamat, Janvier 2017
Introduction: Industrial context for Short Fibers Reinforced Plastics (SFRP)

Structural scale

- Flow
- Gradients induced by the process and/or the environment

Processing
- Fatigue defects population

Environment
- Fatigue mechanisms

Thermomechanical loading

Macromolecules

Semi-crystalline microstructure

Colloque National d’Aussois, Mécamat, Janvier 2017
Introduction: Industrial context for Short Fibers Reinforced Plastics (SFRP)

Characterization on samples

Processing

Environment

Thermomechanical loading

Complex mechanical tests

Cyclic constitutive law

Wöhler Curves

Fatigue initiation criterion

Local strain, stress and energy fields

Validation of the prototype

Support of thermal measurements ??

DIFFICULTY N°1

DIFFICULTY N°2

DIFFICULTY N°3
Outline of the presentation

1. Toolbox and Evaluation of dissipation from thermal measurements

2. Some answers to industrial expectations
   - Supply data to feed or validate design computation loops
   - Fast screening of fatigue properties for various parameters
   - Fast diagnostic on structural samples and parts

3. Questions, limits and tracks to move further
   - Illustration of some questions and limits
   - Analysis based on constitutive modeling
   - Analysis based on the evaluation of defects populations
   - Thermomechanical evaluation at the microscopic scale

4. Conclusions
Outline of the presentation

1. Toolbox and Evaluation of dissipation from thermal measurements

2. Some answers to industrial expectations
   - Supply data to feed or validate design computation loops
   - Fast screening of fatigue properties for various parameters
   - Fast diagnostic on structural samples and parts

3. Questions, limits and tracks to move further
   - Illustration of some questions and limits
   - Analysis based on constitutive modeling
   - Analysis based on the evaluation of defects populations
   - Thermomechanical evaluation at the microscopic scale

4. Conclusions
Thermal measurements?

Defects detection

Physical constants

Microscopic field measurements

Acoustic solicitation, Lock-In thermography, Laser pulse, …

Thermo elasticity and Quantitative calorimetry under mechanical loading

Taylor and Quinney (1934)

Anthony (1942)

Treloar (1975)

Joule (1850)

A. Chrysochoos et al.

D. Rittel

GDR CNRS 2519 « Mesures de champs et identification en mécanique des solides » et « Calorimétrie quantitative en mécanique des matériaux »
Evaluation of dissipation from thermal measurements: the toolbox

- Infrared Camera Lens 50mm and “G1”
- Testing machines
- X-ray Micro Tomograph
- SEM with EDS
- Environmental testing conditions
- Various temperatures and humidities
- Classical and interrupted fatigue tests

Initiation criterion
Measuring accurately temperature is fine …

but here, we seek dissipation!

Homemade pixelwise calibration

[Belenos®, V. Le Saux]

Thermal resolution < 10 mK differential measurements

Spatial resolution 1 pixel ~ 15 µm

Evaluation of dissipation from thermal measurements: the toolbox
Evaluation of dissipation from thermal measurements: the approaches

\[ \rho c \dot{T} + \text{div}(\overline{q}) = \Delta + r + \rho T \frac{\partial^2 \Psi}{\partial V_k \partial T} \dot{V}_k + \rho T \frac{\partial^2 \Psi}{\partial \varepsilon^e \partial T} : \varepsilon^e \]

Evolution along time
Exchange and diffusion
Intrinsic dissipation
Reflection from external sources
Couplings between internal variables \( V_k \)
Thermo-elastic couplings

Local equation.
It is mandatory to consider the same volume

Surface measurements vs volumic sources:
ill conditioned problem

For large displacements, the convective term of the time derivative can be important
Evaluation of dissipation from thermal measurements: the approaches

\[ \rho c \dot{T} + \text{div}(\dot{q}) = \Delta + r + \rho T \frac{\partial^2 \Psi}{\partial V_k \partial T} \cdot \dot{V}_k + \rho T \frac{\partial^2 \Psi}{\partial \varepsilon^e \partial T} : \varepsilon^e \]

**Evolution along time**
- Exchange and diffusion
- Intrinsic dissipation
- Reflection from external sources

**Couplings between internal variables** $V_k$

**Thermo-elastic couplings**

**Fit of thermal functions**
- Direct numerical fit
- Decomposition in functions (usually Fourier’s)
- Assumptions on the function shape, based on mechanical and thermal hypotheses

**Hypotheses on spatial sources dissipation**

**Hypotheses on temporal evolution**
- Stationary thermal state
- Analysis at the limits of transient states
- Adiabatic
- Average analysis over a cycle
- Constant cyclic source
Evaluation of dissipation from thermal measurements: the approaches

\[ \rho c \dot{T} + \text{div}(\mathbf{q}) = \Delta + r + \rho T \frac{\partial^2 \Psi}{\partial V_k \partial T} \dot{V}_k + \rho T \frac{\partial^2 \Psi}{\partial \varepsilon^e \partial T} : \dot{\varepsilon}^e \]

**Evolution along time**
- Exchange and diffusion
- Intrinsic dissipation
- Reflection from external sources
- Couplings between internal variables \( V_k \)
- Thermo-elastic couplings

**Fit of thermal functions**
- Direct numerical fit
- Decomposition in functions (usually Fourier’s)
- Assumptions on the function shape, based on mechanical and thermal hypotheses

**Sources assumptions**
- Spatial distribution of \( S(t) \)
- Assumptions on the function shape, based on mechanical and thermal hypotheses
- Thermomechanical model based analysis

**Hypotheses on spatial sources dissipation**

**Hypotheses on temporal evolution**
- Stationary thermal state
- Analysis at the limits of transient states
- Adiabatic
- Average analysis over a cycle
- Constant cyclic source

**Direct experimental evaluation of the sources from thermal fields**
Evaluation of dissipation from thermal measurements: the approaches

\[ \rho c \dot{T} + \text{div}(\vec{q}) = \Delta + r + \rho T \frac{\partial^2 \Psi}{\partial V_k \partial T} \cdot \dot{V}_k + \rho T \frac{\partial^2 \Psi}{\partial \varepsilon^e \partial T} : \dot{\varepsilon}^e \]

Evolution along time, Exchange and diffusion, Intrinsic dissipation, Reflection from external sources, Couplings between internal variables, Thermo-elastic couplings

Considering \( \theta = T - T_{\text{reference}} \)

\[ \rho c \dot{\theta} + \text{div}(\vec{q}) = \Delta + r + \rho \theta \frac{\partial^2 \Psi}{\partial V_k \partial T} \cdot \dot{V}_k + \rho \theta \frac{\partial^2 \Psi}{\partial \varepsilon^e \partial T} : \dot{\varepsilon}^e \]

Low dependency of \( V_k \) on temperature variations

The external radiation supply is considered constant

The thermo-elastic couplings compensate over a mechanical cycle

Low temperature variations \( \Delta T \sim 0.2^\circ C \)

Small temperature variations \( \Delta T \sim 2^\circ C \)
Evaluation of dissipation from thermal measurements: the approaches

\[ \rho c \dot{\theta} + \text{div}(\overrightarrow{q}) = \Delta = fr. \Delta^* \]

Use the stationary state

the mean dissipation per cycle is constant

Identify \( \tau_{eq} \)
Evaluation of dissipation from thermal measurements: the approaches

\[
\rho c \dot{\theta} + \text{div}(\mathbf{q}) = \Delta = \text{fr. } \Delta^* 
\]

Sources assumptions:
- Spatial distribution of S(t)
- Assumptions on the function shape, based on mechanical and thermal hypotheses
- Thermomechanical model based analysis

1. Identify \( \tau_{eq} \)
2. \( \Delta^* = \frac{\rho c \dot{\theta}}{\text{fr} \tau_{eq}} \)
Evaluation of dissipation from thermal measurements: the approaches

\[ \rho c \theta + div(\mathbf{q}) = \Delta = fr \Delta^* \]

Sources assumptions:
- Spatial distribution of \( S(t) \)
- Assumptions on the function shape, based on mechanical and thermal hypotheses
- Thermomechanical model based analysis

Stationary state profiles

Inverse identification by FE

Validation

Use the stationary state

[Poster T. Glanowski]
Evaluation of dissipation from thermal measurements: the approaches

\[ \rho c \hat{\dot{\theta}} + \text{div}(\hat{\theta}) = \tilde{\Delta} = f_r \Delta^* \]

\[ \Delta^* = \frac{\rho C \hat{\dot{\theta}}_0}{f} \]
Evaluation of dissipation from thermal measurements: the approaches

\[ \rho c \dot{\theta} + \text{div}(q) = \Delta = fr \cdot \Delta^* \]

Direct mapping of the dissipated energy \( \Delta^* \)

Over a given thickness depending on thermal exchanges vs mechanical frequency
Evaluation of dissipation from thermal measurements: the approaches

Evaluation from the transient state

\[ \Delta^* = \frac{\rho C \dot{\theta}_0}{f} \]

Temperature difference

\( \dot{\theta}_0 \)

Temps

Evaluation from the stationary state

\[ \Delta^* = \frac{\rho C \bar{\theta}_{sta}}{f \tau_{eq}} \]

Temperature difference

\( \bar{\theta}_{sta} \)

Temps [s]

Stress amplitude

Temperature

Energie dissipée par cycle [MJ/m³]

Transitent state

Stationary state

Amplitude de contrainte nominale [MPa]
Outline of the presentation

- Evaluation of dissipation from thermal measurements and heat build-up curve

2 Some answers to industrial expectations

- Supply data to feed or validate design computation loops
- Fast screening of fatigue properties for various parameters
- Fast diagnostic on structural samples and parts

Questions, limits and tracks to move further

- Illustration of some questions and limits
- Analysis based on constitutive modeling
- Analysis based on the evaluation of defects populations
- Thermomechanical evaluation at the microscopic scale

Conclusions
Overview for SFRP

**Goal:** to take into account the local microstructure to evaluate the local mechanical properties and to predict both the global stiffness and local fatigue criterion.

**Complex mechanical tests**

**Cyclic constitutive law**

**Processing**

**Environment**

**Thermomechanical loading**

**DIFFICULTY N°1**

Characterization on samples
Constitutive model for SFRP

- Anisotropic model to account for the gradients induced by the process

Injection computation (MoldFlow©)

Fibers orientation

Mesh Interpolation (Digimat-MAP©)

Anisotropic mechanical properties

FE simulation (UMAT Abaqus©)
Constitutive model for SFRP: model proposal and identification

Phenomenological modeling

1. Short term visco-elasticity
   \( E^0_e, E_{v2}, \eta_2 \)

2. Long-term Visco-elasticity
   \( E_{v1}, \eta_1 \)

3. Non-linear Visco-plasticity
   \( A, H, m, C, \gamma \)

4. Softening parameters \( a, b \)
Correlation between simulations and experiments

\[ D_1 = A_{v1} : \dot{\varepsilon}_{v1} + A_{v2} : \dot{\varepsilon}_{v2} + A_{vp} : \dot{\varepsilon}_{vp} + X : \dot{\varepsilon} + A_\beta \cdot \dot{\beta} \]

Sources assumptions:
- Spatial distribution of S(t)
- Assumptions on the function shape, based on mechanical and thermal hypotheses
- Thermomechanical model based analysis

\[ \Delta^* = \frac{1}{f_r} \int_{cycle} D_{int} \, dt \]

Strain fields

Dissipation fields

Constitutive model for SFRP: challenge on experiments on structures
Constitutive model for SFRP: challenge on experiments on structures

Next step: inverse analysis but here more confidence is needed on the microstructure!
How to evaluate fastly the fatigue properties??

Characterization on samples

Compounding and Processing

Environment

Thermo-mechanical loading

Complex mechanical tests

Cyclic constitutive law

Difficultie N°2

Wöhler Curves

Fatigue initiation criterion

Local strain, stress and energy fields

Fatigue approach based on a stabilized cycle

Energy based criterion

Very fast evaluation
How to evaluate fastly the fatigue properties: Heat build-up protocols

Principle and history of heat build-up tests

- **Le commencement**
  - Auto-échauffement
  - \( \theta = \theta(N) \)
  - Méthode empirique
  - \( \sigma_d \)

- **La traversée du désert**
  - Méthode empirique
  - Structures
  - Mesures infrarouges
  - Multiaxial

- **Le renouveau**
  - Modélisation
  - A.E. ➔ Fatigue
  - Identification
  - Structures

- **La modélisation**

[Source: Munier]

Colloque National d’Aussois, Mécamat, Janvier 2017
How to evaluate fastly the fatigue properties of rubber compounds???

Characterization on samples

Compounding and Processing

Environment

Thermo-mechanical loading

1. Fatigue approach based on a stabilized cycle
2. Energy based criterion
3. Very fast evaluation

DIFFICULTY N°2

Complex mechanical tests
Cyclic constitutive law

Wöhler Curves
Fatigue initiation criterion

Local strain, stress and energy fields
How to evaluate fastly the fatigue properties of rubber compounds

- Given compound and process
- Given geometry
- Testing conditions

Fast evaluation

- Potential sites location
- Inclusions size scattering
- Local mechanical loading

Initiation criterion at a local scale

Energy based fatigue criterion

Temperature based analysis

Fatigue properties

Map of dissipated energy (experimental or numerical)

Activated sites locations
Heat build up protocol

Displacement | Energy
---|---

NR 43 CB N550

50mm | G1

Energy dissipated per cycle [μJ/mm³]

Local maximum principal strain (%)
Questions on the heat build-up curve

**Evaluation over which volume?**

\[ e = \sqrt{\frac{\rho C_p}{\lambda \pi f}} = 1.06 \text{ mm at 2Hz} \]

**Consistent with damage location?**

- Yes

**Repeatable?**

- Yes

**Dissipated energy**

- Num. mean at the skin
- Num. mean over 1 mm
- Experiment

**Local maximum strain (%)**

**Dissipated energy**

- Local maximum strain (%)
Fast identification of an energy based criterion

1- First pair
\((\Delta_B, N_B)\)

Strain / energy assumed to lead to a \(10^6\) cycles lifetime

2- Second pair
\((\Delta^*_G, 10^6)\)

Determination from a graphical evaluation

Energy model

\[ \Delta^* \cdot N^b = C \]

Two pairs \((\Delta, N)\)

Analytical identification of the 2 model parameters

\[
\begin{align*}
  b &= 0.467 \\
  C &= 14437
\end{align*}
\]
Fast identification of an energy based criterion

Math relation:
\[ \Delta^* = \Delta^*(\varepsilon) \]

Energy model
\[ \Delta^* \cdot N^b = C \]

- \( b = 0.467 \)
- \( C = 14437 \)

\[ \Delta^*(\varepsilon) \cdot N^b = C \]

\[ N = f(\varepsilon) \]
Proposal and challenge of an energy-based fatigue criterion

Energy model

\[ \Delta^* \cdot N^b = C \]

\[ b = 0.467 \]
\[ C = 14437 \]

\[ \Delta^*(\epsilon) \cdot N^b = C \]

\[ N = f(\epsilon) \]

How to evaluate fastly the fatigue properties of rubber compounds???
How to evaluate fastly the fatigue properties of rubber compounds ???

Proposal and challenge of an energy-based fatigue criterion

Energy model

\[ \Delta^* \cdot N^b = C \]

- \( b = 0.467 \)
- \( C = 14437 \)

Clear identification, validation on the whole (deterministic) curve satisfying

Very quick evaluation of the criterion

(2 days, 1 sample)
Challenge of the approach on other compounds

Variation of the fillers ratio:

Variation of the fillers type:
Challenge of the approach on other compounds

Global comparison

→ Very fast and efficient prediction of the fatigue curves for various compounds
How to evaluate fastly the fatigue properties of SFRP???

- Characterization on samples
- Processing
- Environment
- Thermomechanical loading
- Complex mechanical tests
- Cyclic constitutive law
- Wöhler Curves
- Fatigue initiation criterion
- Local strain, stress and energy fields

**DIFFICULTY N°2**

1. Fatigue approach based on a stabilized cycle
2. Energy based criterion
3. Very fast evaluation
Application to SFRP

- Fatigue lifetime
  \[ \Delta \cdot N^b = C \]
  - 1 sample
  - 1 day
- Extensometer
- Force
- Surface Temperature
- Force

- Mean dissipated energy
- Heat build-up curve
- Dissipated energy
- Dissipated Energy criterion
- Classical fatigue tests
- Power law

Colloque National d’Aussois, Mécamat, Janvier 2017

41 / 70
Application to SFRP: Dogbone samples, various orientations

Stress amplitude (Mpa)

Orientation: 0°

Orientation: 45°

Orientation: 90°

Cycles to initiation

Orientation: 0°

Orientation: 45°

Orientation: 90°
Application to SFRP: Dogbone samples, various environments (T°C, RH)

\[ T - T_g > 0 \]

- \( T_g \)
- T23°C-RH80
- T23°C-RH50
- T60°C-RH50
- T80°C-RH50

Graphs showing temperature vs. humidity ratio and cycles vs. Δ*.
Overview for SFRP

Characterization on samples

Complex mechanical tests

Cyclic constitutive law

Wöhler Curves

Fatigue initiation criterion

Local strain, stress and energy fields

Validation of the prototype

Processing

Thermomechanical loading

Environment

Difficulties N°3
Application to SFRP: Structural samples and parts

Structural samples are designed to generate specific microstructure and loadings, representative of the ones met on parts.
Application to SFRP: Structural samples and parts

f=1Hz, R=0, RH50, Ambient.

Dogbone 0° Wavy 1

Dogbone 0° Wavy 2
Application to SFRP: Structural samples and parts

X+ direction

X- direction
Application to SFRP: Structural samples and parts
Outline of the presentation

Evaluation of dissipation from thermal measurements and heat build-up curve

Some answers to industrial expectations

- Supply data to feed or validate design computation loops
- Fast screening of fatigue properties for various parameters
- Fast diagnostic on structural samples and parts

Questions, limits and tracks to move further

- Illustration of some questions and limits
- Analysis based on constitutive modeling
- Analysis based on the evaluation of defects populations
- Thermomechanical evaluation at the microscopic scale

Conclusions
Questions, limits and tracks to move further

1. Energy based criterion is good but can be improved

\[
(\Delta W_{\text{diss}} + \alpha P_{\text{max}}) \cdot N_a^b = C'
\]

[Amiable, Launay]

- Unification OK for several 
  \( R > 0 \), but not if \( R < 0 \)
- Dependancy on the loading shape
- Dependancy on the loading history (creep+fatigue, here)

Constitutive models + Probabilistic approach

2. Describe the fatigue scattering
   Improve the prediction of the mean curve

- Use microstructural data
- Defects population
- Link between dissipation and fatigue mechanisms

3. Go beyond a threshold analysis for these materials exhibiting no clear fatigue limit
   Validate the extrapolation over \( 10^6 \) cycles
Tracks to move further: Analysis based on constitutive modeling

1. Better description of the hysteresis
2. Better link to the damage mechanisms

(source: C. Doudard)

(source: H. Rolland)
Tracks to move further: Analysis based on the evaluation of defects populations

Given compound and process
Given geometry
Testing conditions

Potential sites location
Inclusions size scattering
Local mechanical loading

Fast evaluation

Use microstructural data
Defects population

Fatigue properties
Energy based fatigue criterion
Map of dissipated energy (experimental or numerical)
Activated sites locations

Temperature based analysis

Colloque National d’Aussois, Mécamat, Janvier 2017
Tracks to move further: Analysis based on the evaluation of defects populations

A given volume under a given load

\[ E_D = \int_0^{N_i} E_{\text{diss},f}(\varepsilon, N) dN \]

\[ E_{\text{diss},f} = \Delta^*(\varepsilon) \omega_d(\varepsilon, N) \]

\[ E_D = \int_0^{N_i} \Delta^*(\varepsilon) \omega_d(\varepsilon, N) dN \]

Energy dissipated per cycle [\( \mu \text{J/mm}^2 \)]

Local maximum principal strain [%]

A given defects population under a given load
Tracks to move further: Analysis based on the evaluation of defects populations

Interrupted fatigue tests

Surfacic defects density

SEM analysis for several zones

For each sample, 3 local max. principal strain studied

Evaluation of the defects surfacic density for Areas 1, (2, 2′), (3, 3′)
Surfacic defects density

Observations: \( \text{Surv} \) depends both on \( N \) and on \( \varepsilon \)

\( \varepsilon \) is the first order factor

Tracks to move further: Analysis based on the evaluation of defects populations
Tracks to move further: Analysis based on the evaluation of defects populations

Surfacic defects density

\[
E_D = \int_0^{N_i} \Delta^*(\varepsilon) \omega_d(\varepsilon, N) dN
\]

\[
E_D = \Delta^*(\varepsilon) \int_0^{N_i} K(\varepsilon). N \ dN
\]

\[
E_D = \Delta^*(\varepsilon) K(\varepsilon) \frac{N_i^2}{2} = C
\]

Challenge of the approach: can \( E_D \) be considered as a constant?

<table>
<thead>
<tr>
<th>( \varepsilon )</th>
<th>( N_i )</th>
<th>( K(\varepsilon) )</th>
<th>( \Delta^*(\varepsilon) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>90%</td>
<td>250 000</td>
<td>1.43.10^{-4}</td>
<td>83</td>
</tr>
<tr>
<td>140%</td>
<td>58 000</td>
<td>1.28.10^{-3}</td>
<td>167.4</td>
</tr>
<tr>
<td>190%</td>
<td>22 000</td>
<td>5.79.10^{-3}</td>
<td>277.3</td>
</tr>
</tbody>
</table>
Tracks to move further: Analysis based on the evaluation of defects populations

\[ E_D = 3.8 \times 10^8 = C' \]

\[ E_D = \Delta^* (\varepsilon) K (\varepsilon) \frac{N^2}{2} \]
Tracks to move further: Thermomechanical evaluation at the microscopic scale

Given compound and process

Given geometry

Testing conditions

Potential sites location

Inclusions size scattering

Local mechanical loading

Fast evaluation

Link between dissipation and fatigue mechanisms

Initiation criterion at a local scale

Fatigue properties

Energy based fatigue criterion

Map of dissipated energy (experimental or numerical)

Activated sites locations

Δ*.N = C
Tracks to move further: Thermomechanical evaluation at the microscopic scale

Local description of initiation sites for filled rubbers: tomo and SEM views

- Polar cavities
- Cavitation between close inclusions
- Break of fillers agglomerates

Precious results ... but providing only a kinematic view!

- Decohesion at one pole
- Decohesion on the sides
- Propagation on the surface and in the volume
Tracks to move further: Thermomechanical evaluation at the microscopic scale

- Infrared Camera
  - Lens 50mm and "G1"
- Electro-dynamical testing machine Bose 3.2kN
- Optical microscope with extension device
- SEM with EDS
  - Micro tension compression device
- Very thin films (200 µm), well or badly mixed compounds
Tracks to move further: Thermomechanical evaluation at the microscopic scale

- Lens “G1”
- Thermal acquisition at 70Hz.

Mechanical protocol

Temperature fields

Dissipated energy fields
Tracks to move further: Thermomechanical evaluation at the microscopic scale

Apparition of two hot spots localised at the crack tips

Hole
Tracks to move further: Thermomechanical evaluation at the microscopic scale

Geometry of the sample

- 20mm
- 7mm
- 0.3 – 0.4 mm

CB agglomerates embedded by matrix

Thermal acquisition at 100Hz with reduced observed zone.

Lens “G1”

Global mean strain of 200%

Dissipated energy fields

<table>
<thead>
<tr>
<th>J/mm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
</tr>
<tr>
<td>0.08</td>
</tr>
</tbody>
</table>

Tracks to move further: Thermomechanical evaluation at the microscopic scale
Tracks to move further: Thermomechanical evaluation at the microscopic scale
Tracks to move further: Thermomechanical evaluation at the microscopic scale

**Geometry of the sample**

- CB agglomerate
- 20mm x 10mm x 0.6mm

**Mechanical protocol**

- Accommodation: 10 cycles - 10Hz
- Cyclic loading: 20 cycles - 10Hz
- Cooling: 120s

- Thermal acquisition at 100Hz with reduced observed zone.

**Lens “G1”**

- Global mean strain of 120%

**Comparison of the geometries: IR and SEM pictures**

**Dissipated energy fields**

- Area of Maximum dissipated energy
- Carbon black inclusion
- Decohesion at the poles
Tracks to move further: Thermomechanical evaluation at the microscopic scale

Temperature fields
Tracks to move further: Thermomechanical evaluation at the microscopic scale

Given compound and process
Given geometry
Testing conditions

Potential sites location
Inclusions size scattering
Local mechanical loading

Fast evaluation
Initiation criterion at a local scale

Fatigue properties
Energy based fatigue criterion
Map of dissipated energy (experimental or numerical)
Activated sites
Outline of the presentation

1. Evaluation of dissipation from thermal measurements and heat build-up curve
2. Some answers to industrial expectations
   - Supply data to feed or validate design computation loops
   - Fast screening of fatigue properties for various parameters
   - Fast diagnostic on structural samples and parts
3. Questions, limits and tracks to move further
   - Illustration of some questions and limits
   - Analysis based on constitutive modeling
   - Analysis based on the evaluation of defects populations
   - Thermomechanical evaluation at the microscopic scale
4. Conclusions
Thank you for your attention

Yann.marco@ensta-bretagne.fr
Références
I. Masquelier. Thèse de doctorat, Université de Bretagne Occidentale. 2014.
V. Le Saux. Thèse de doctorat. Université de Bretagne Occ. 2010.