

# INFRARED THERMOGRAPHY FOR MATERIAL FATIGUE CHARACTERIZATION

Pr. Vincent LE SAUX *(and many others)*

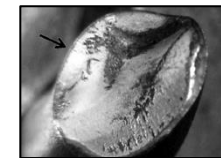
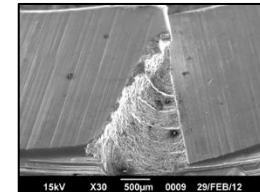
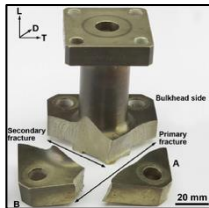
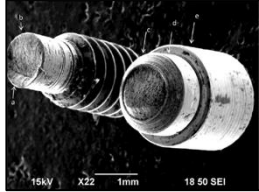
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**IRD**, UMR CNRS 6027, **ENSTA**, Institut Polytechnique de Paris, Bretagne INP, Univ. Brest, Univ. Bretagne Sud, Brest, France.

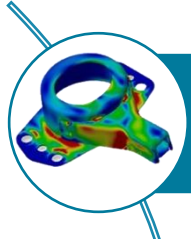
# OUTLINE

1. Motivations
2. SIC from IR measurements
3. Fatigue crack closure detection

# 1. Motivations

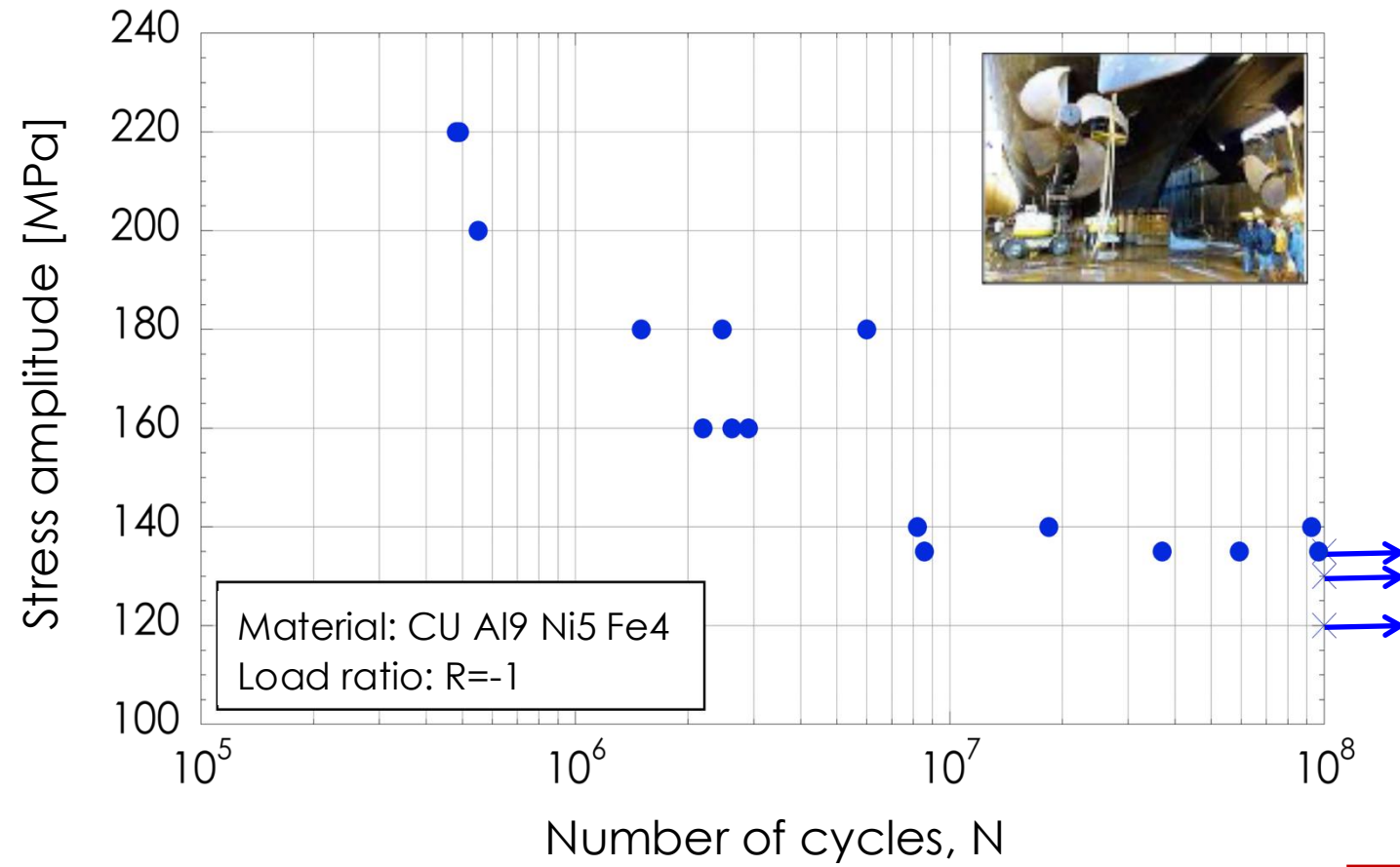


**Fatigue**  
involved in more than  
**60 %**  
of failure in service



A key consideration in part design

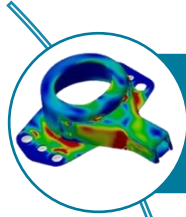
# 1. Motivations



74 days!



# 1. Motivations

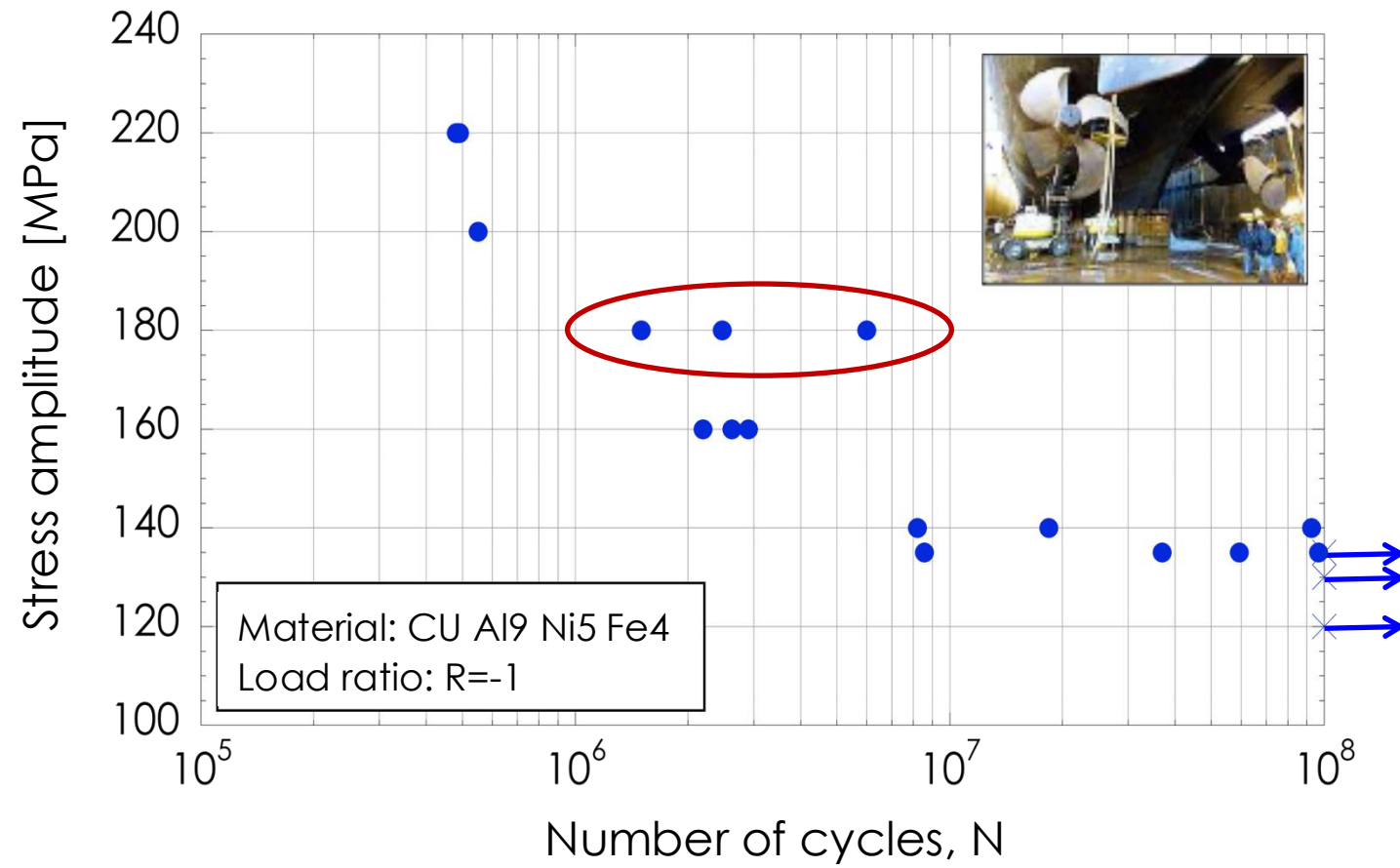


A key consideration in part design

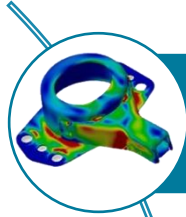


A time consuming activity

# 1. Motivations



# 1. Motivations



A key consideration in part design



A time consuming activity

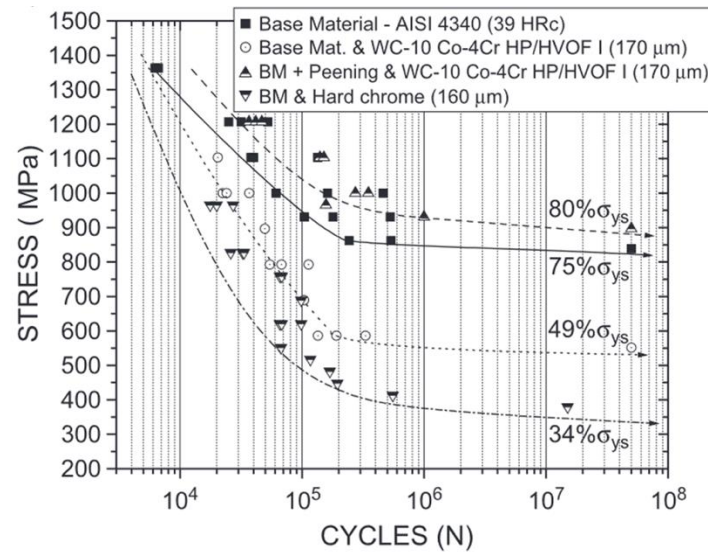
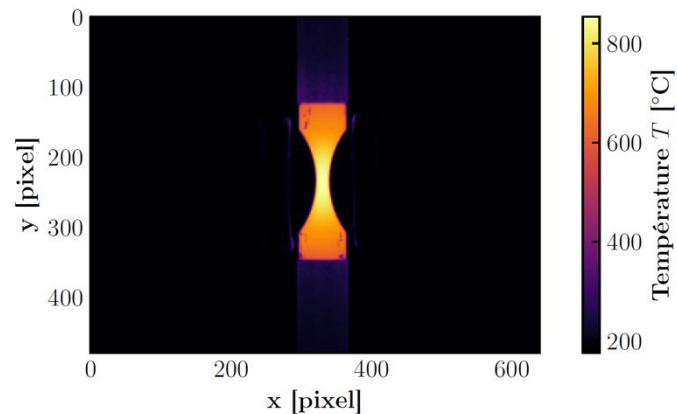
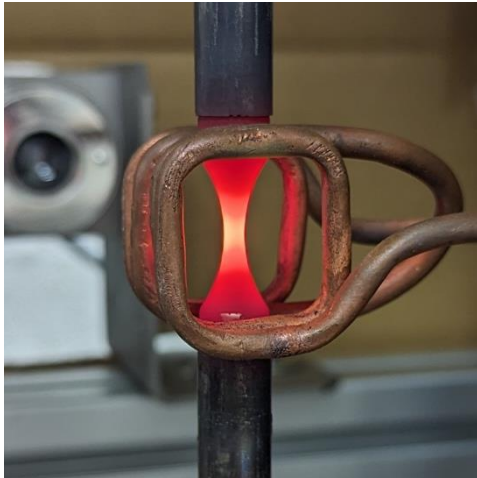


A scattered phenomenon

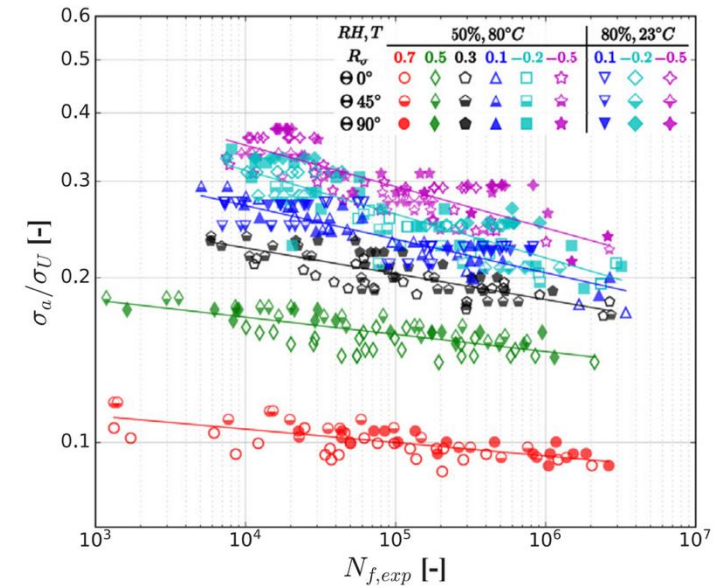


# 1. Motivations

Fatigue properties depend on numerous parameters



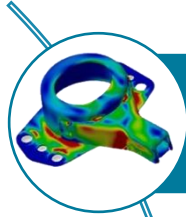
Voorwald et al. (2005)



**Vibracoustic**

Santharam et al. (2020)

# 1. Motivations



A key consideration in part design



A time consuming activity

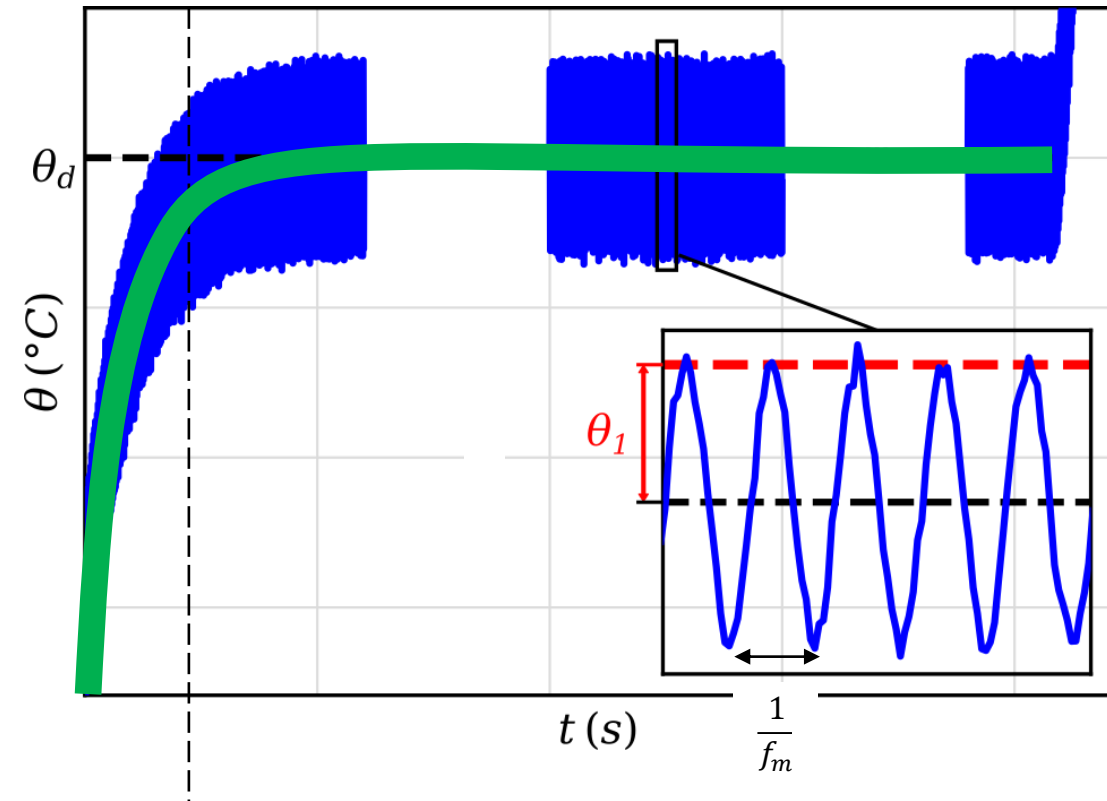
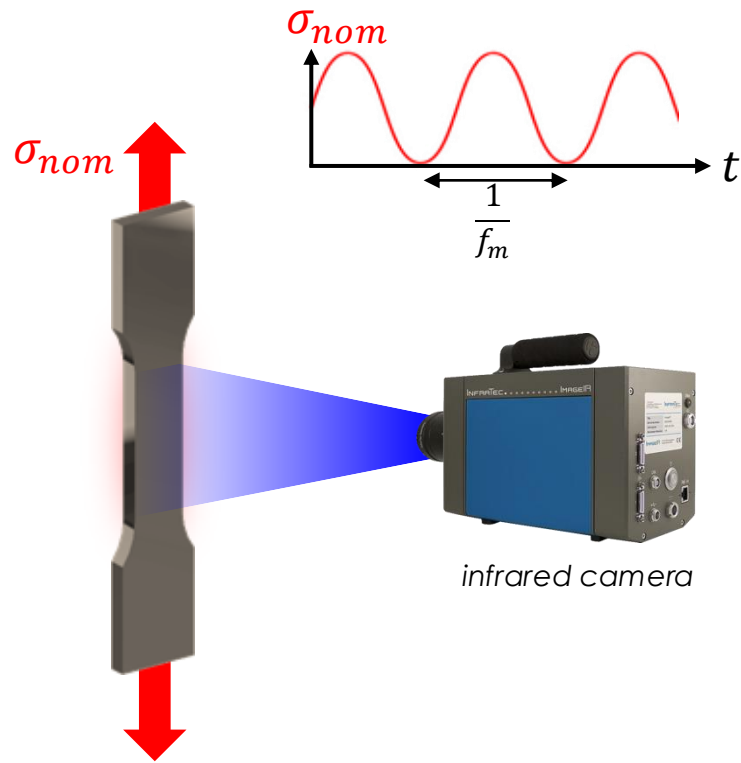


A scattered phenomenon



... that depends on numerous parameters

# 1. Motivations



Local heat equation

**Temperature variation**  
Can be measured



$$\rho c_p \dot{T} + \text{div}(\vec{q}) = \Delta + r + \rho T \frac{\partial^2 \Psi}{\partial \underline{\underline{\varepsilon}} \partial T} : \underline{\underline{\dot{\varepsilon}}} + \sum_k \rho T \frac{\partial^2 \Psi}{\partial V_k \partial T} : \dot{V}_k$$



**Heat sources**  
Cannot be measured

# OUTLINE

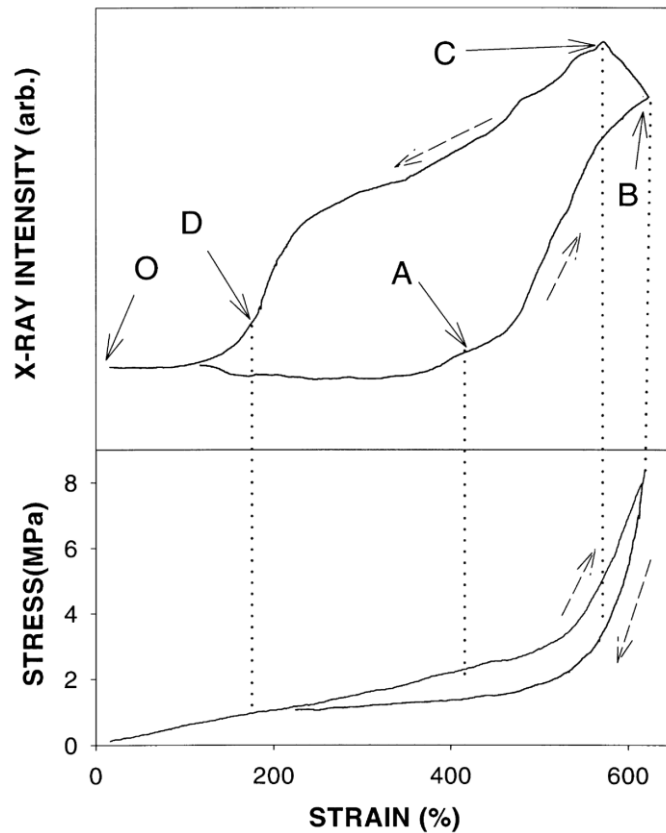
1. Motivations
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PhD of A. Le Bihan (defended in 2025)

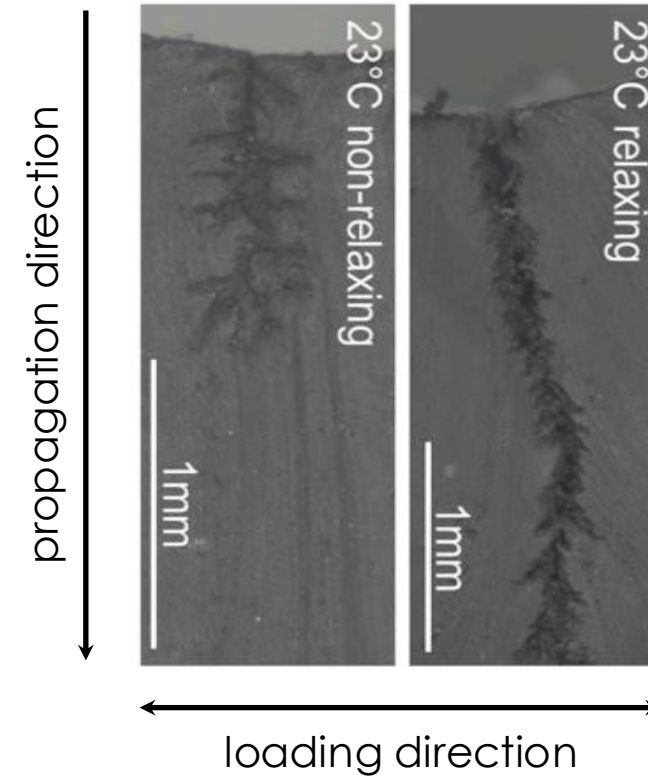




## What is Strain Induced Crystallization?



Toki et al. (2000)

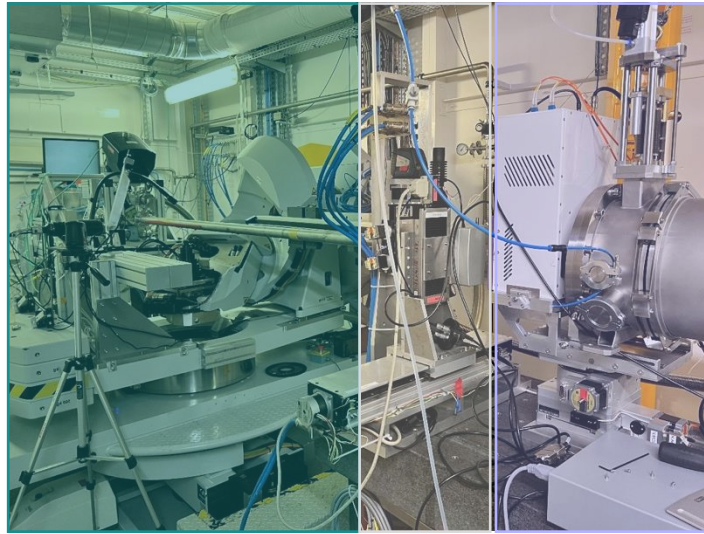


Warneboldt et al. (2022)



# SIC from IR measurements

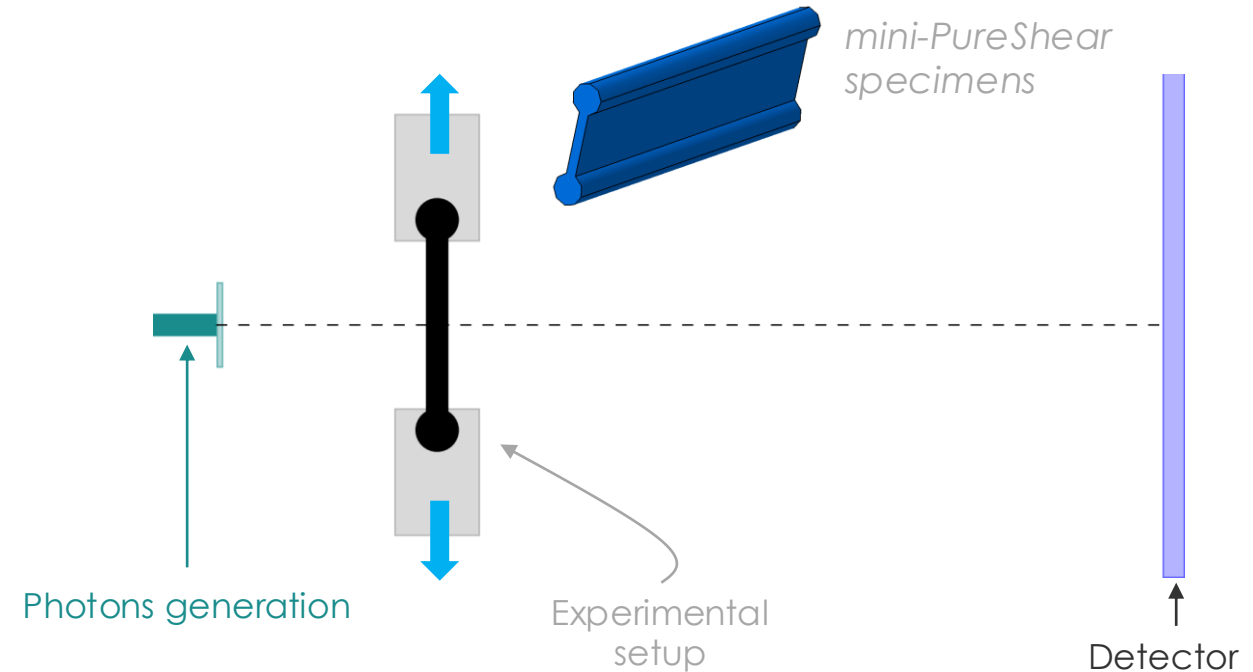
## The classic approach to access crystallinity: WAXD



Photons generation → Experimental setup → Detector



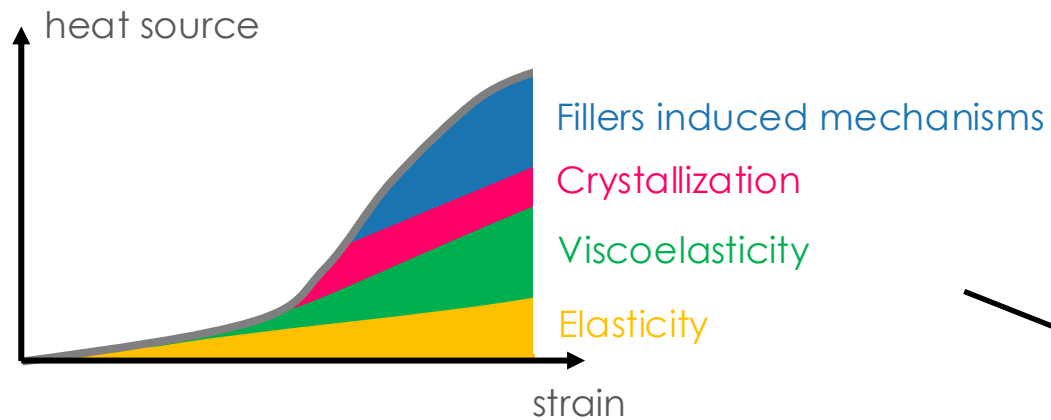
- Access quite difficult
- Difficult to process the data
- Not a full-field technique
- Not really real-time



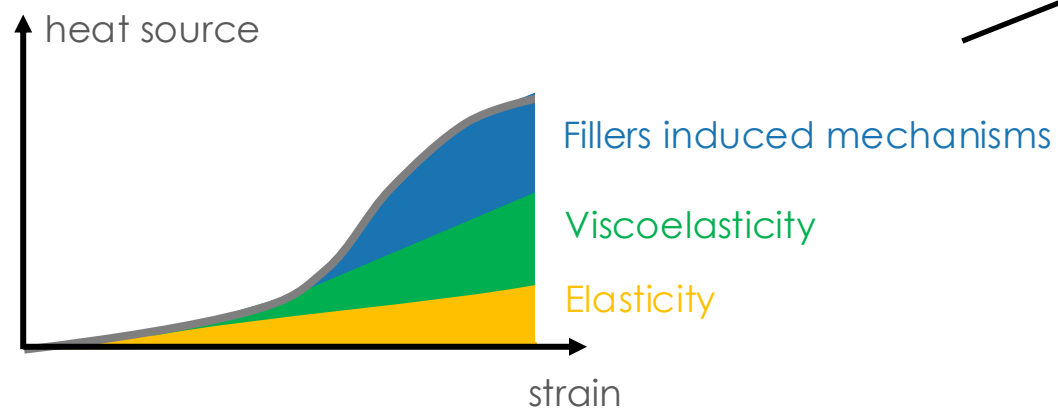
- Phase transformation comes with energetic effects ;
- Infrared calorimetry :
  - Large FPA
  - High frequencies

## The non crystallizing twin approach

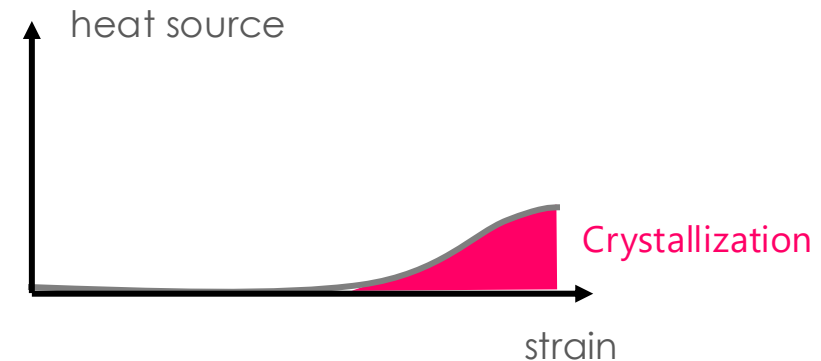
### Reference material, NR42



### Non crystallizing twin, IR42

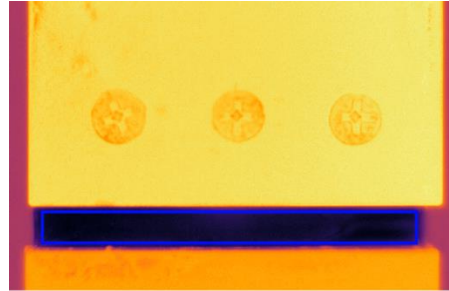
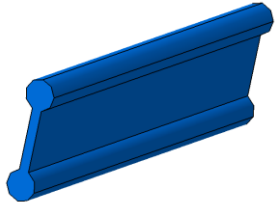


How can we extract the crystallization contribution?



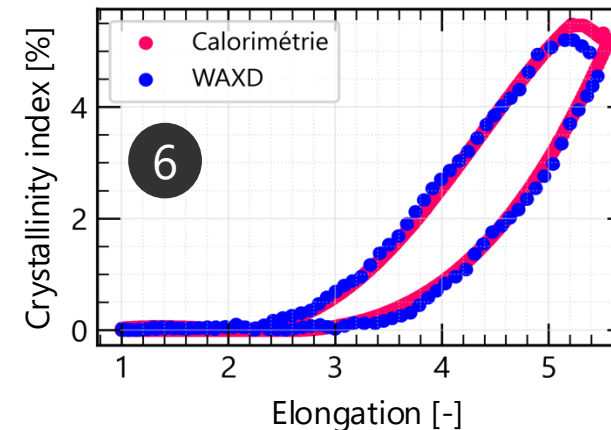
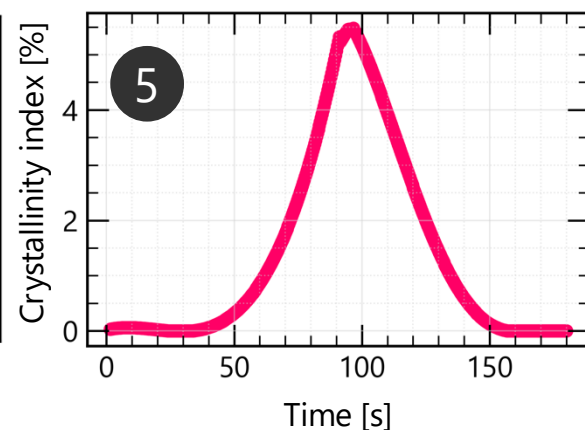
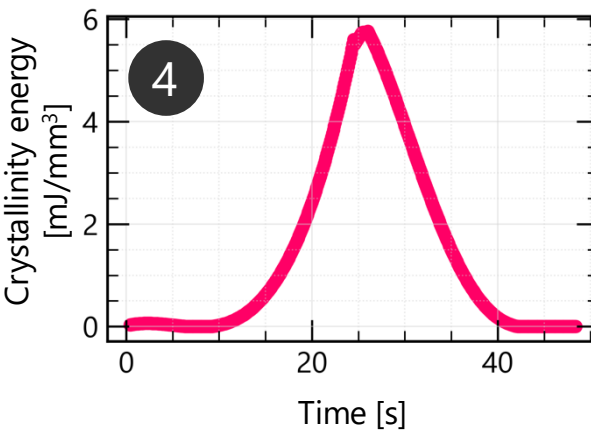
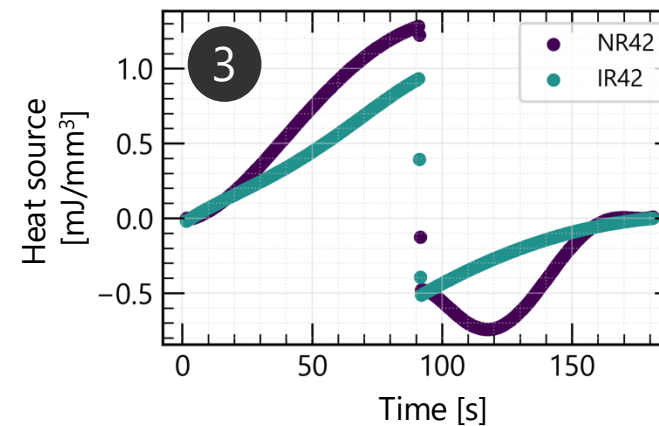
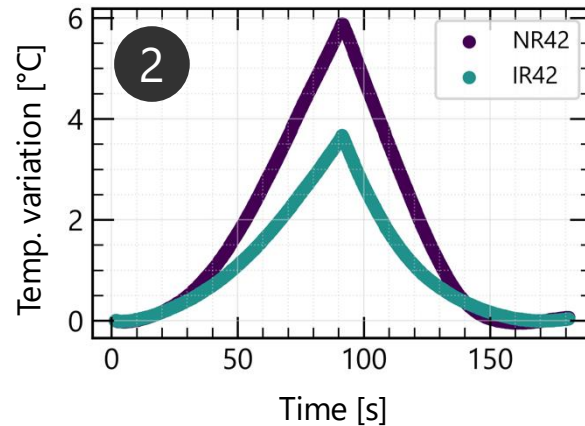
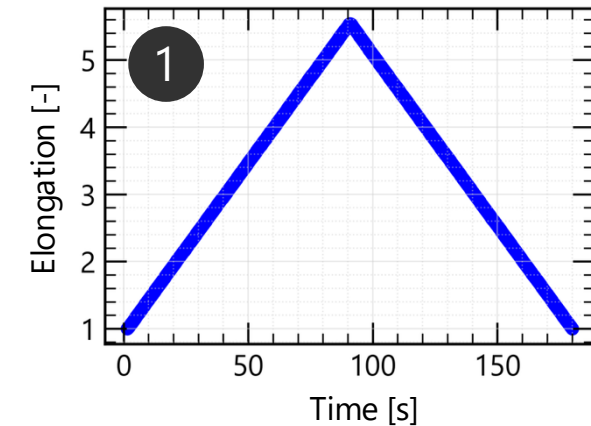
- Use a model
- Find an experimental « hack »

## A simple case



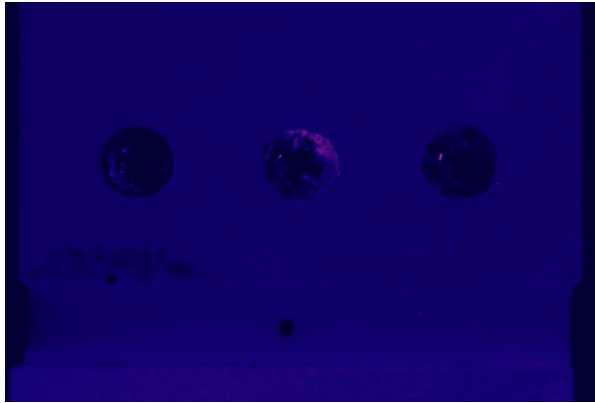
Simplified 0D heat equation

$$\rho c_p \left( \dot{\theta}(t) + \frac{\theta(t)}{\tau_{eq}(t)} \right) = S_t(t)$$

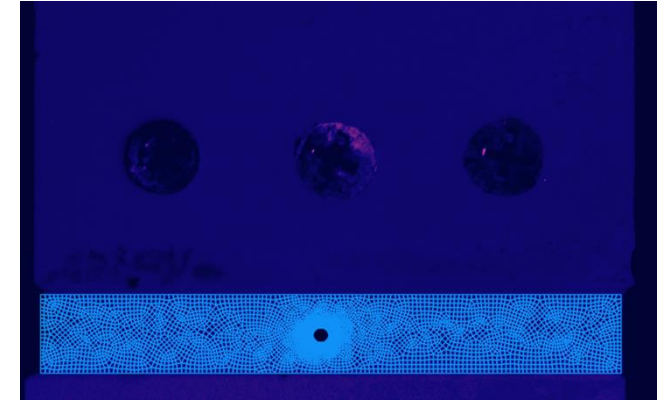
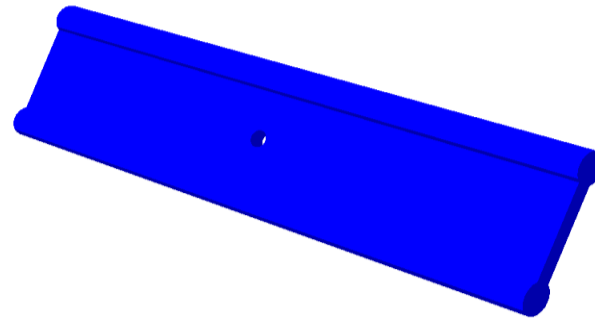


- 1 Mechanical loading
- 2 Thermal signals,  $\theta_{NR42}$ ,  $\theta_{IR42}$
- 3 Heat sources,  $S_{t,NR42}$ ,  $S_{t,IR42}$
- 4 Crystallization energy,
 
$$\int_0^t (S_{t,NR42} - S_{t,IR42}) dt$$
- 5 Crystallinity index,
 
$$\chi_c = \frac{\int_0^t S_{t,crist}(t) dt}{(1 - \phi) \Delta H_0}$$
- 6 WAXD comparison

## A more complex case



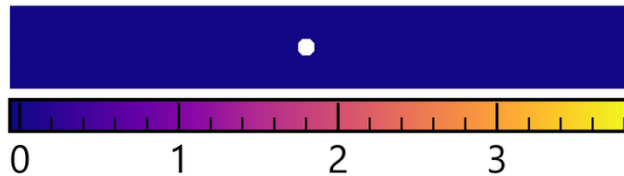
1 pixel  $\neq$  1 particle of matter



1 pixel = 1 particle of matter



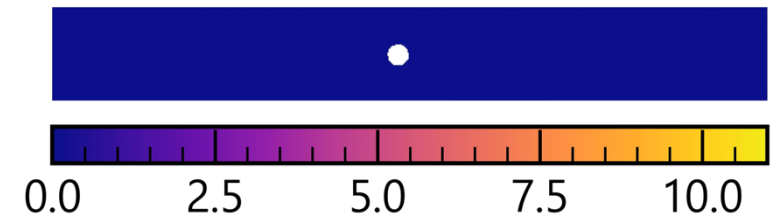
$$S_{t,2D}(x, y, t) = \rho c_p \left( \dot{\theta}_{2D}(x, y, t) + \frac{\theta_{2D}(x, y, t)}{\tau_{eq,2D}(x, y, t)} \right) - \lambda \left( \frac{\partial^2 \theta_{2D}(x, y, t)}{\partial x^2} + \frac{\partial^2 \theta_{2D}(x, y, t)}{\partial y^2} \right)$$



Temperature variation [°C]



non crystallizing twin approach

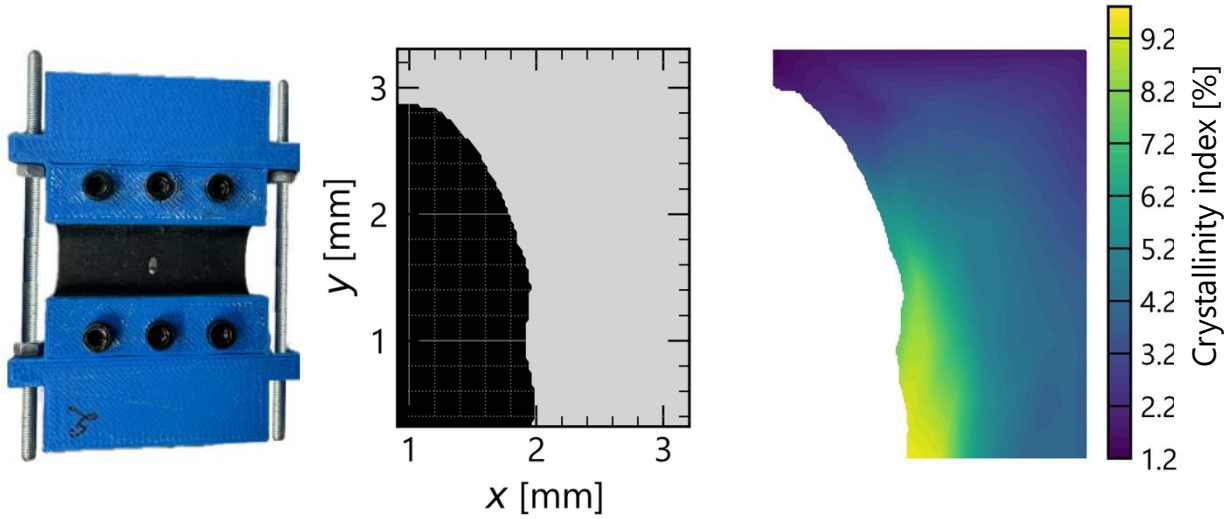


Crystallinity index [%]

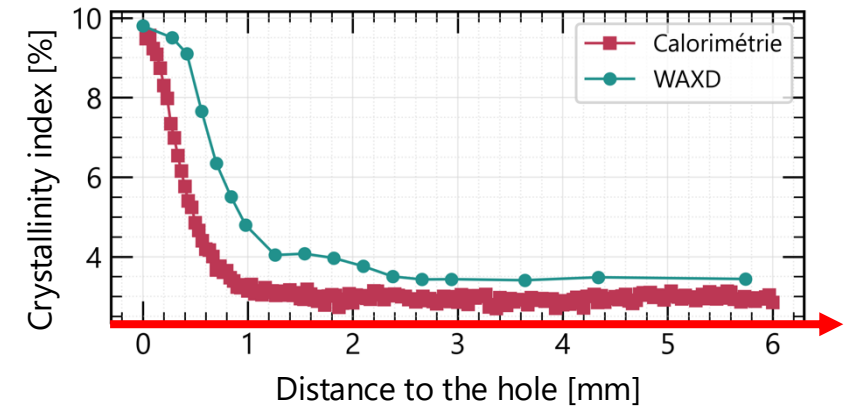
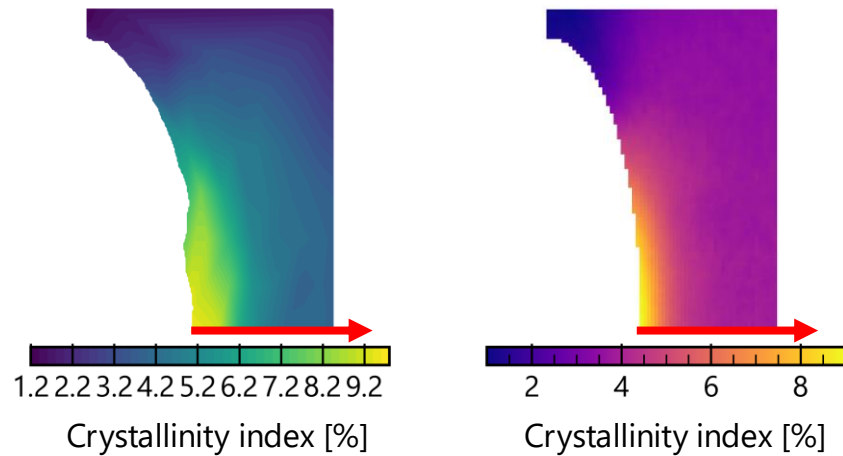
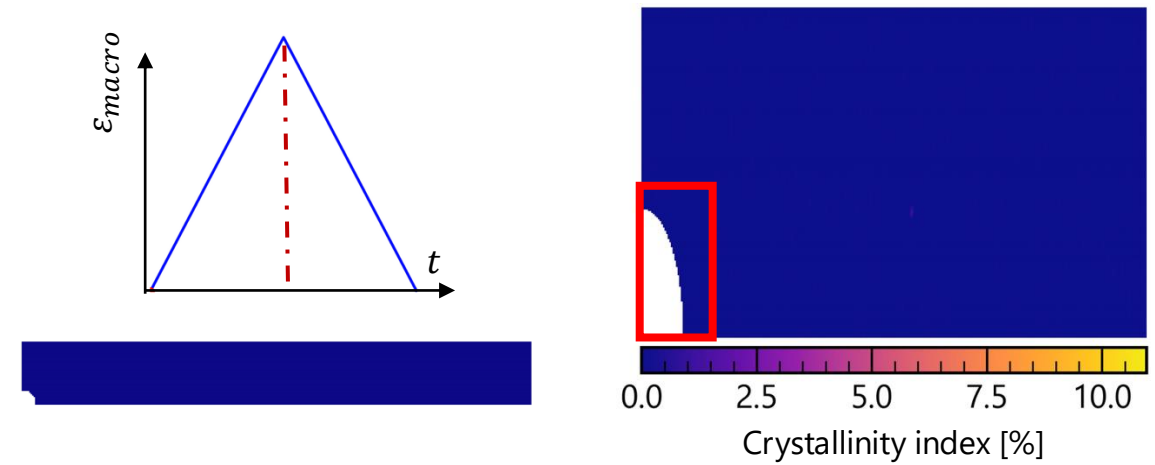


# SIC from IR measurements

WAXD



Infrared calorimetry

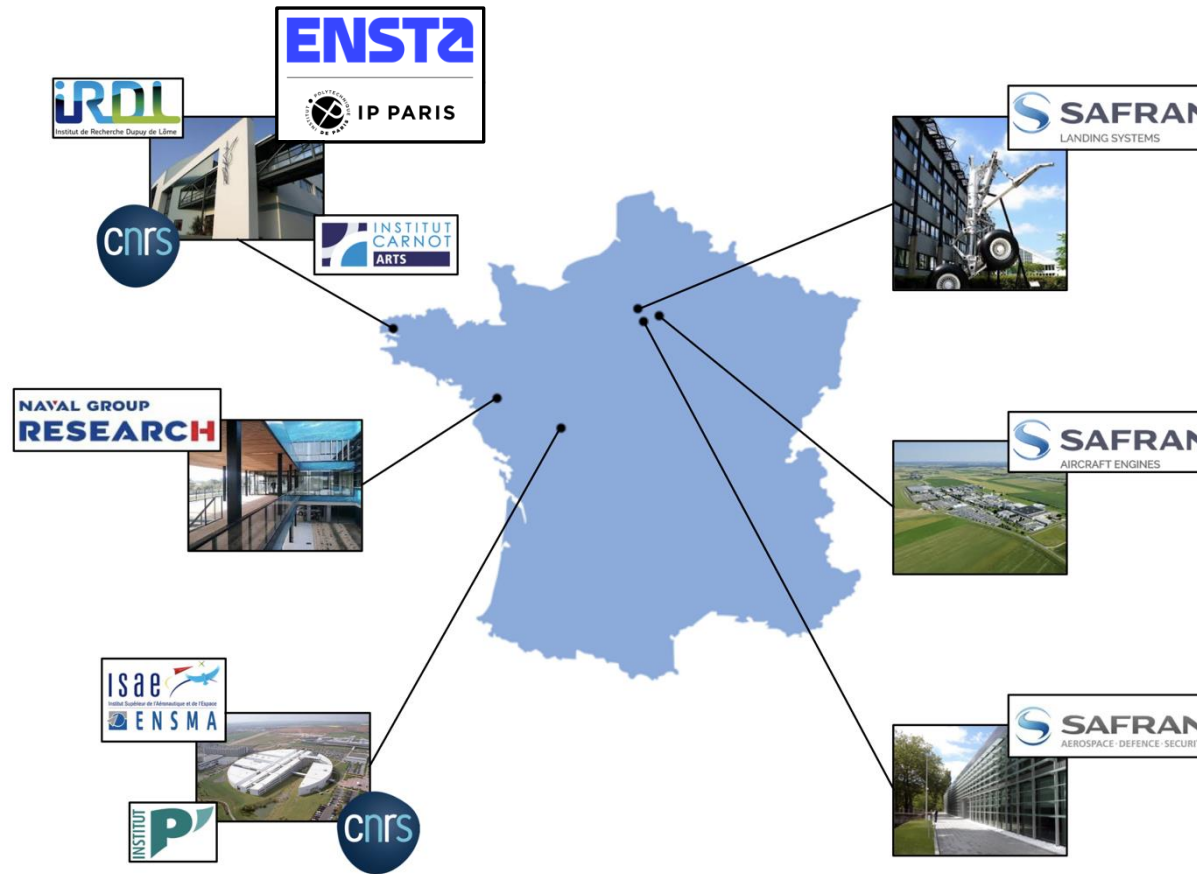


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# Fatigue crack closure and TSA

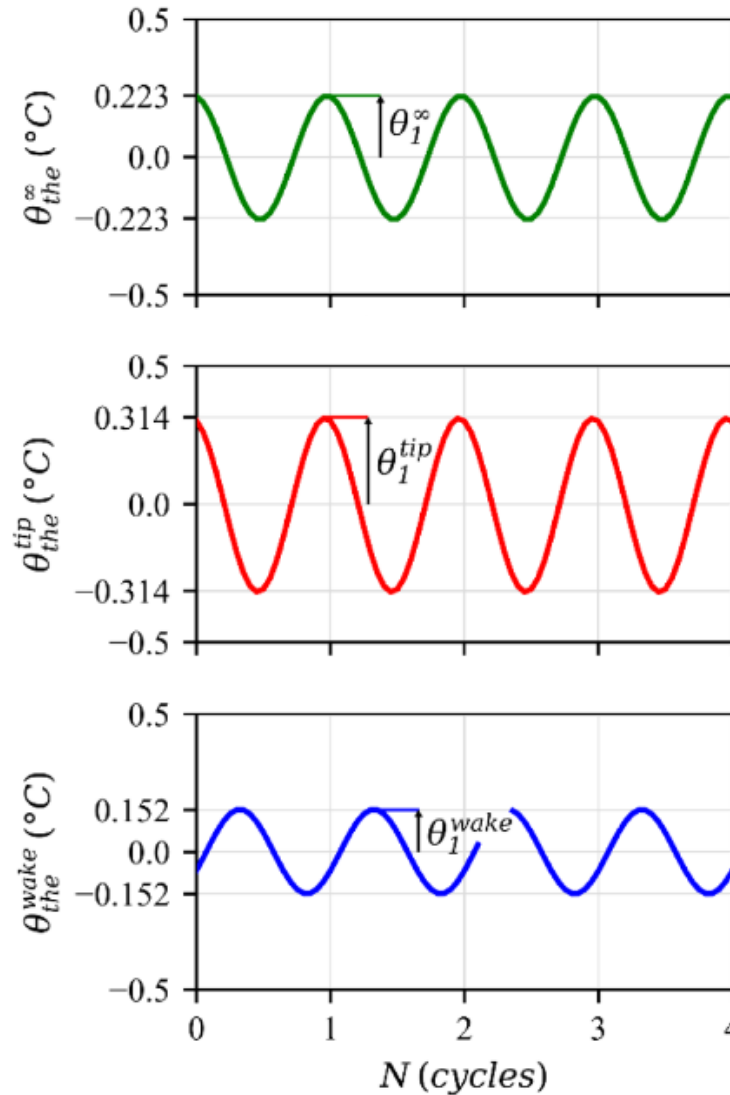
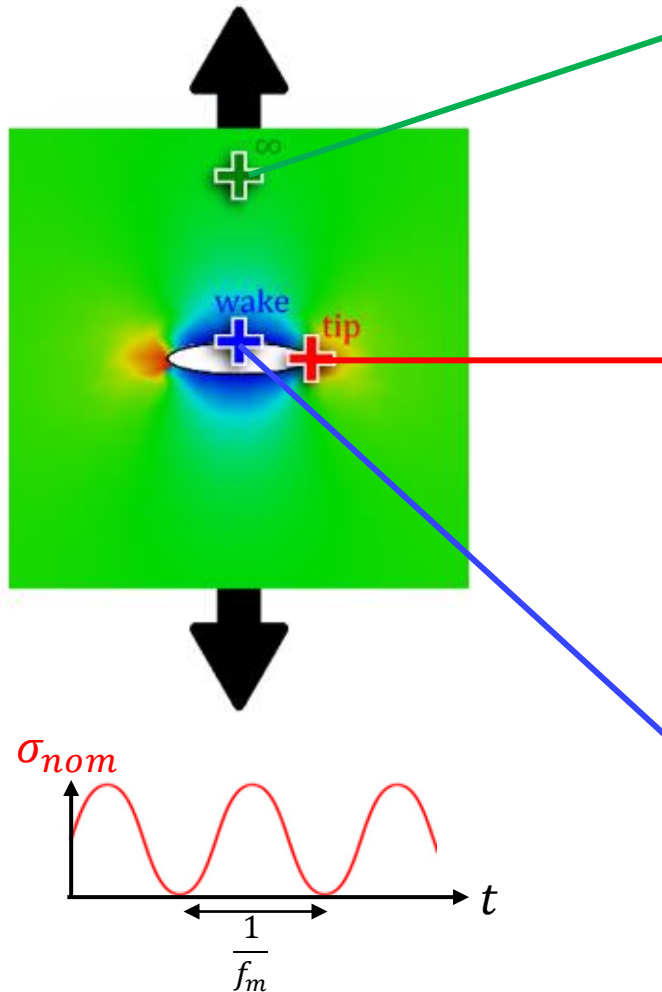


Work done by Dr. L.  
Bercelli

# Fatigue crack closure detection

## Open crack detection with TSA

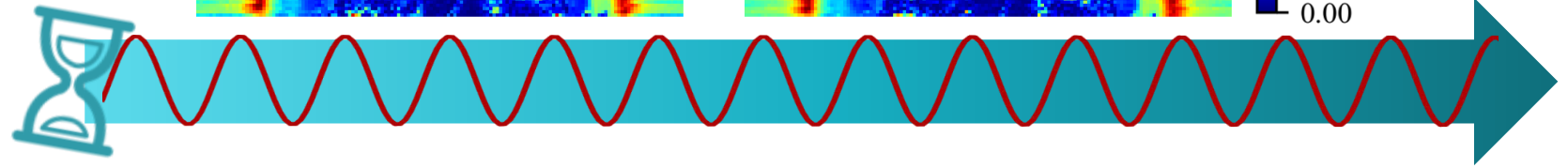
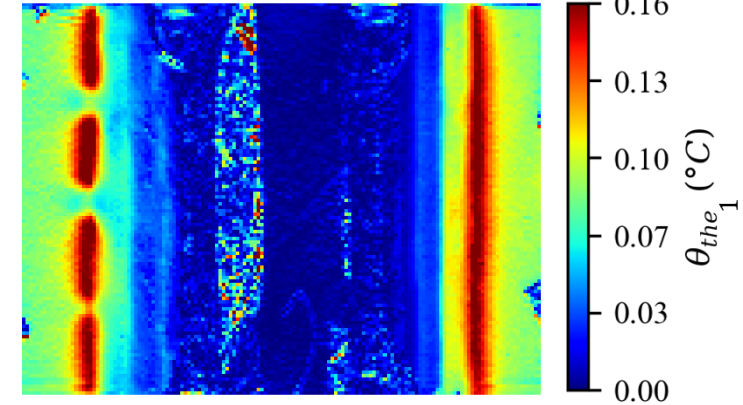
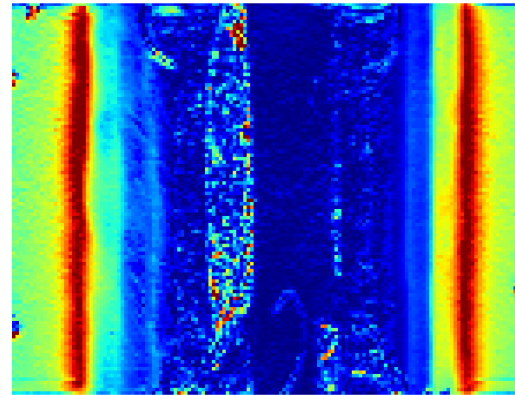
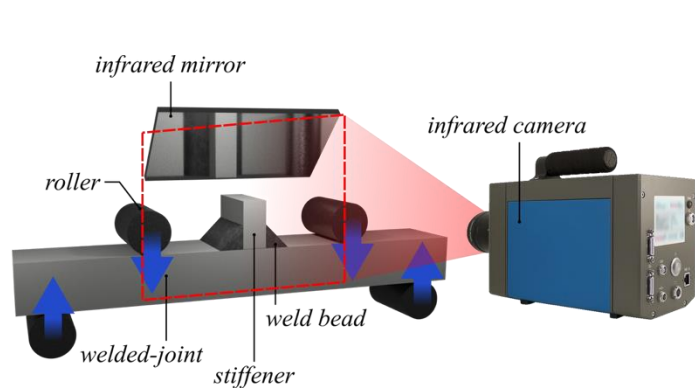
Positive load ratio ( $0 \leq R < 1$ )  
Sine loading



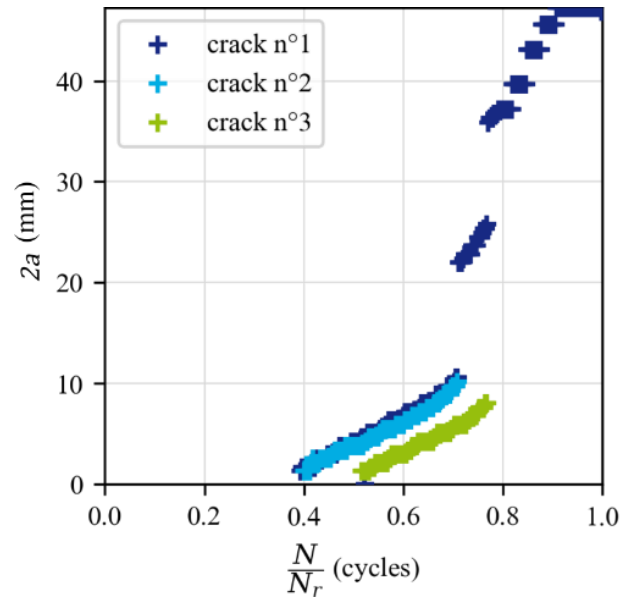
$\theta_1^{tip} > \theta_1^{\infty} \gg \theta_1^{wake}$

**Cracks** can easily be detected with the **first harmonic amplitude** field

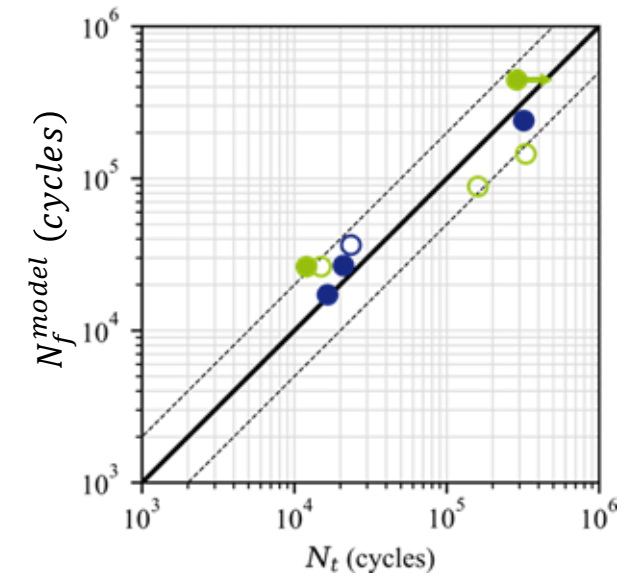
# Fatigue crack closure detection



Individual  
propagation  
curves

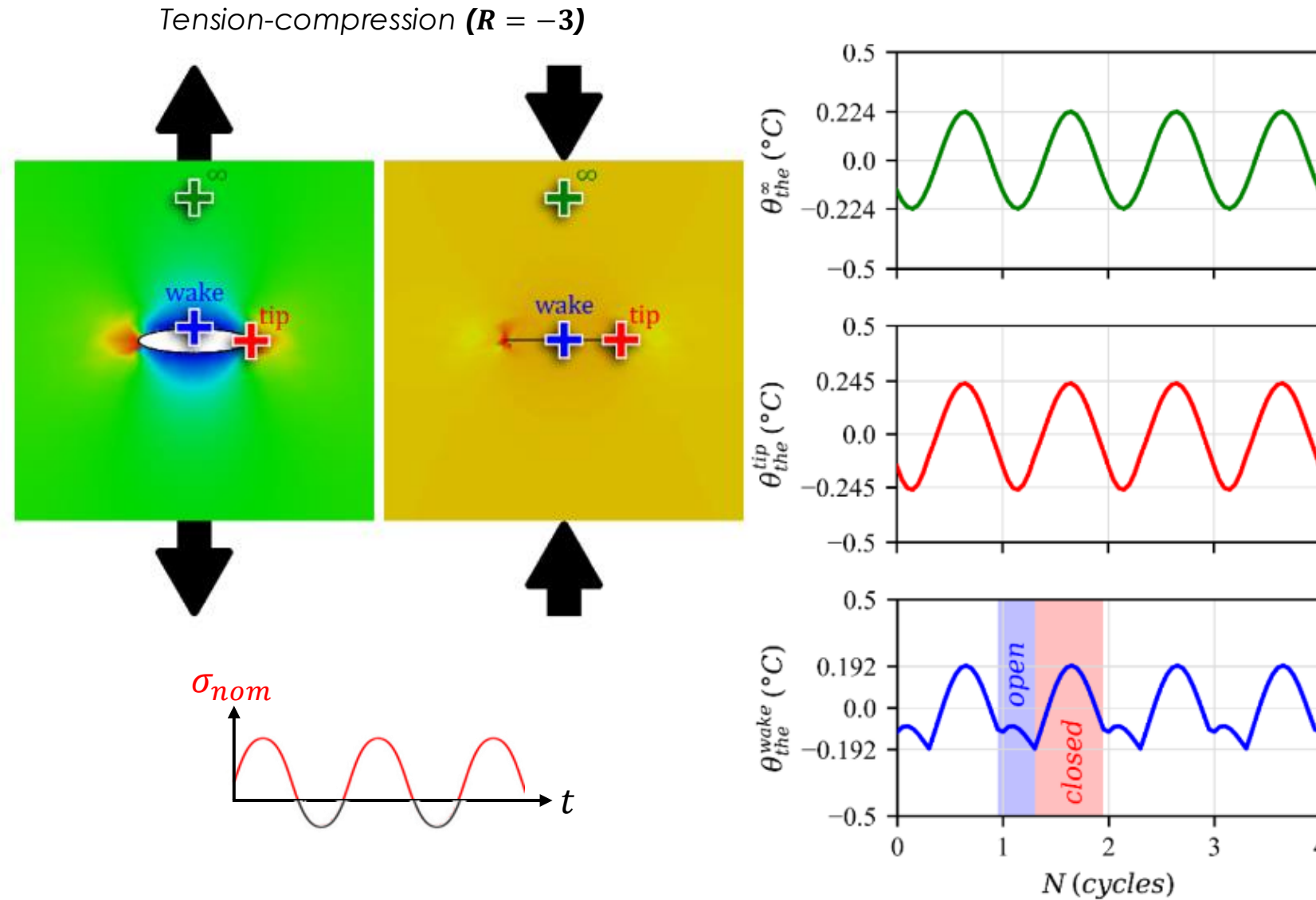


Fatigue lives  
forecast via a  
Paris law



# Fatigue crack closure detection

## Crack detection with TSA in the case of crack closure



A sine loading leads to a non sine temperature evolution

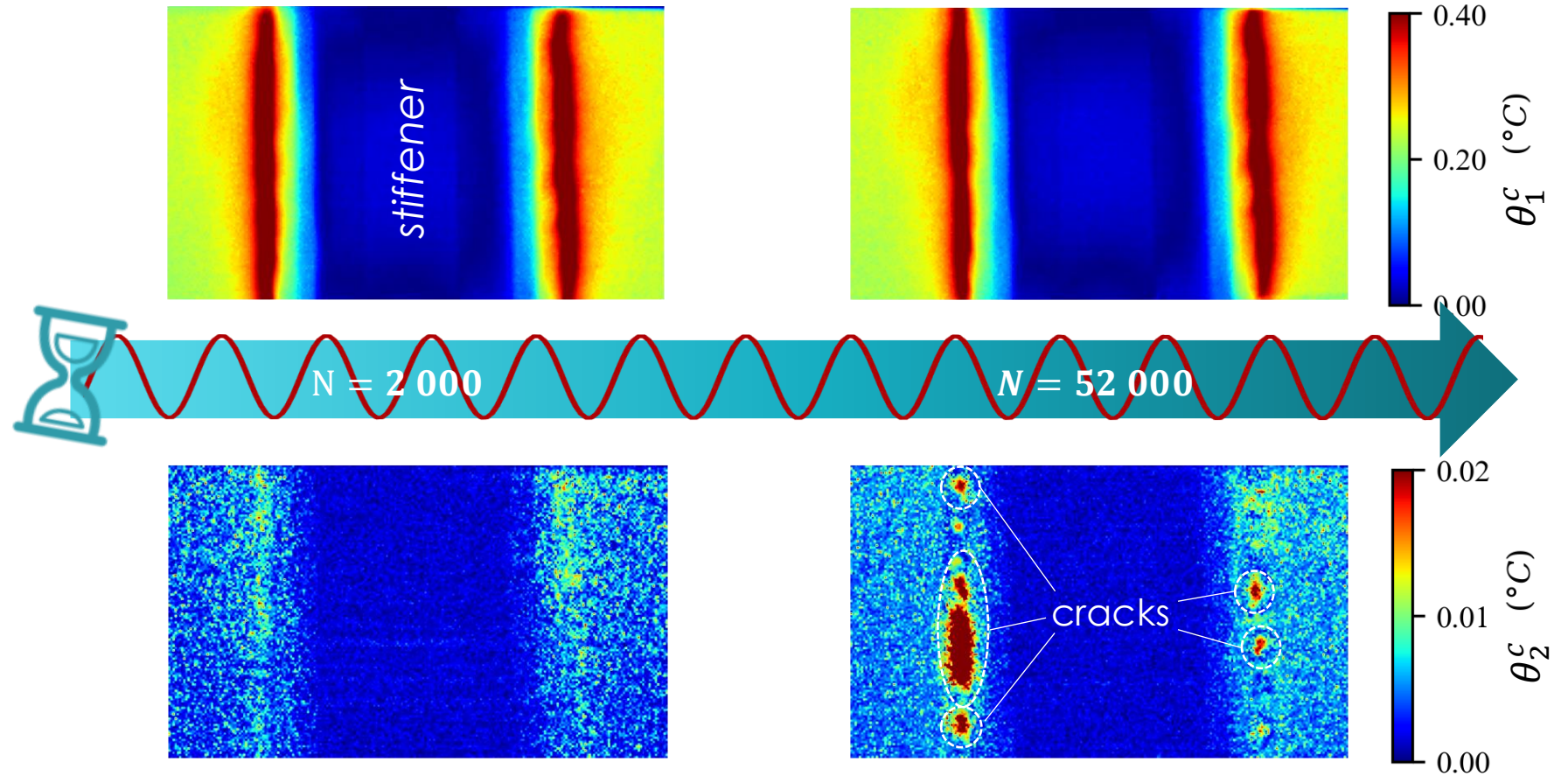
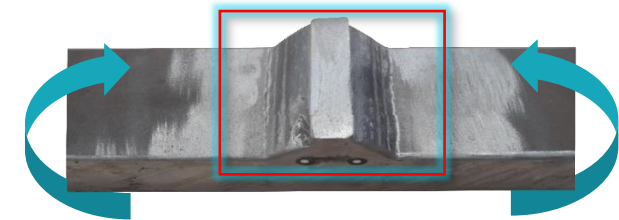
$$\theta_2^{tip} = \theta_2^{\infty} = 0$$
$$\theta_2^{wake} \neq 0$$



# Fatigue crack closure detection

## Crack detection with TSA in the case of crack closure

Tension-compression  
( $R_{loc} < 0$ )



## Crack closure time determination

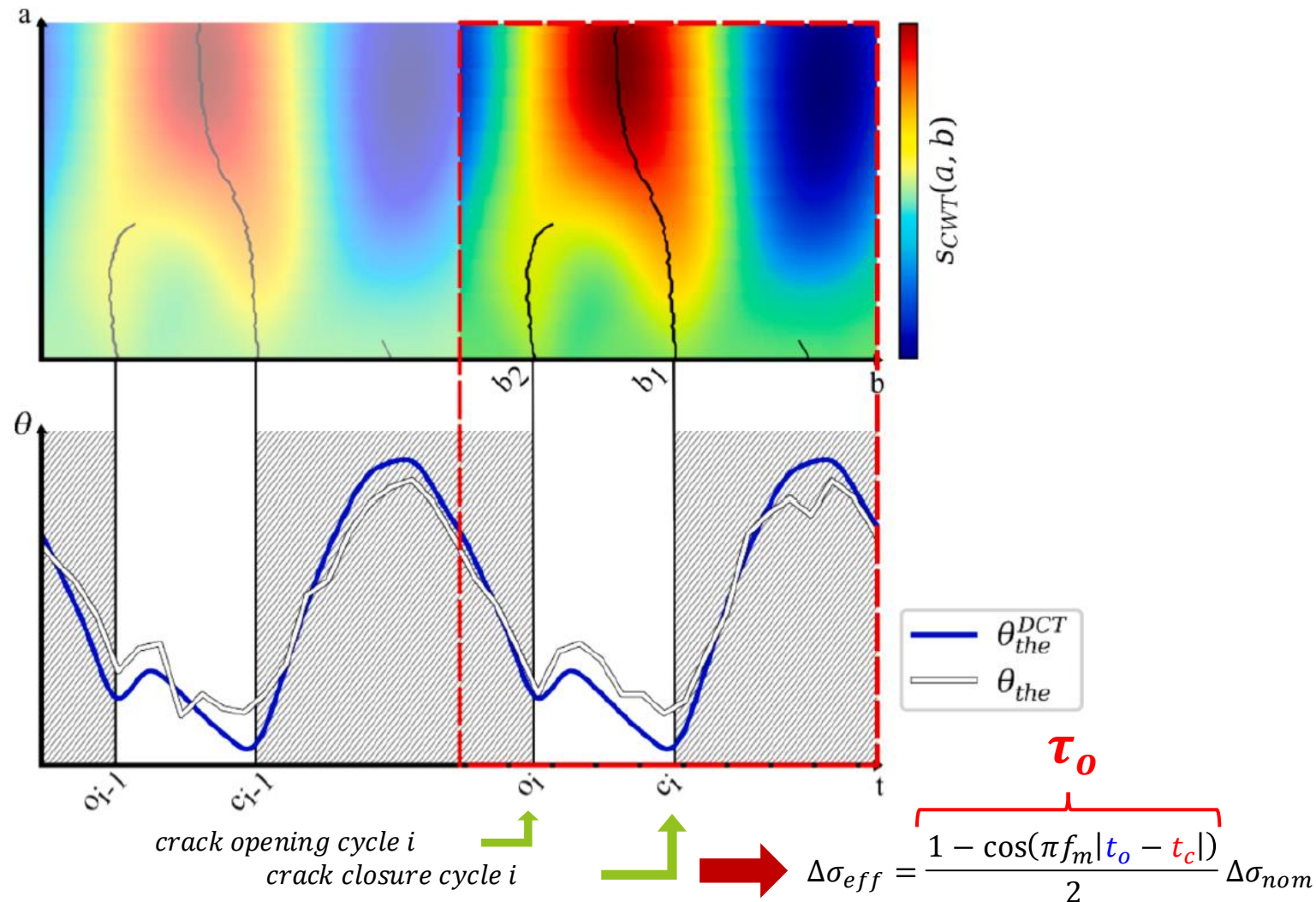
Second step :

Use of the CWT (Continuous Wavelet Transform) to detect crack opening and closure

$$S_{CWT}(a, b) = - \int_{-\infty}^{+\infty} \theta_{the}^{DCT}(t) \times \psi_{a,b}(t) dt$$

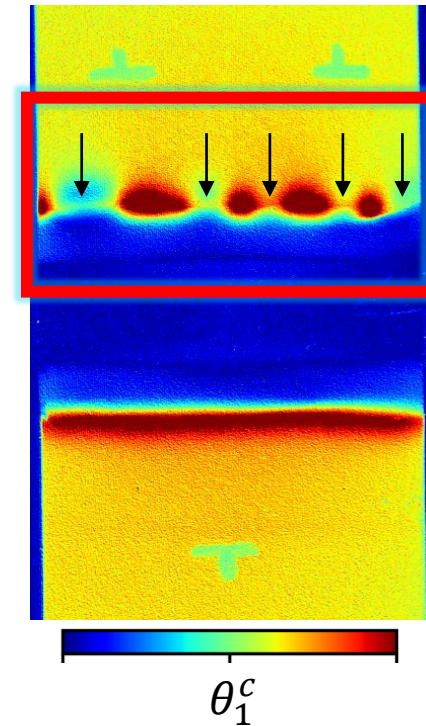
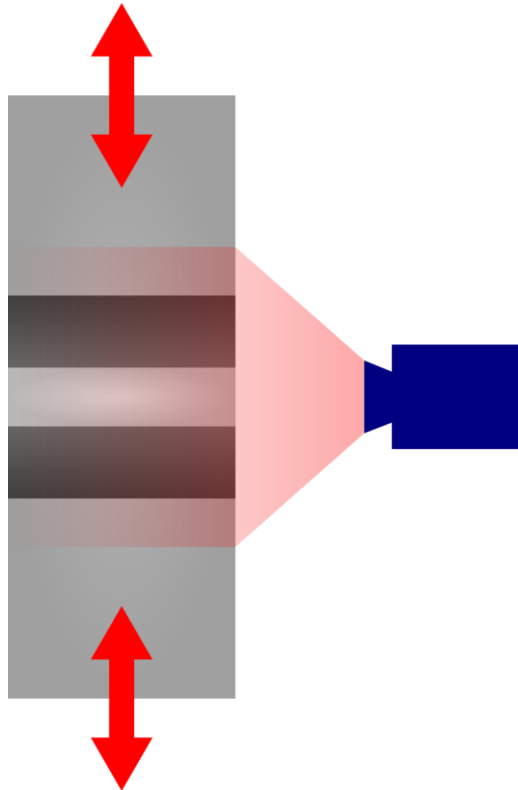
First step :

Reconstruction of the temporal signal (for each pixel) using DCT (Discret Cosine Transform)

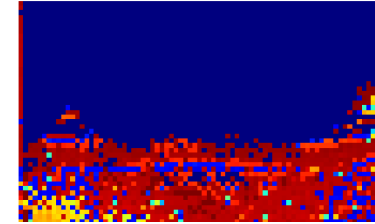




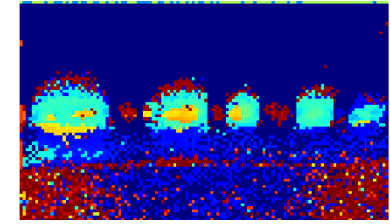
## Crack closure time determination



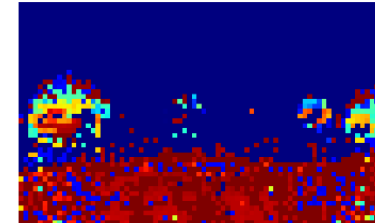
$$R_{nom} = 0$$



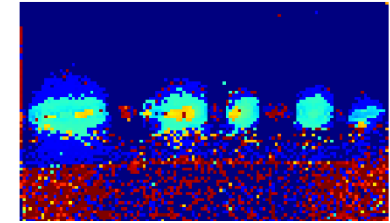
$$R_{nom} = -10$$



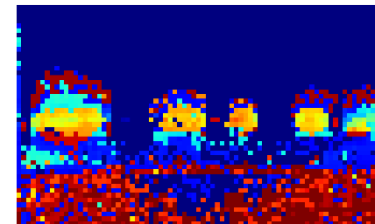
$$R_{nom} = -1$$



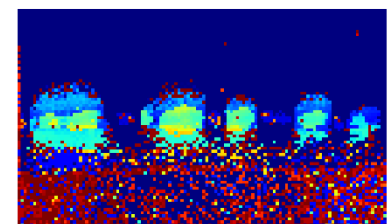
$$R_{nom} = -20$$



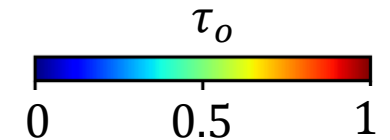
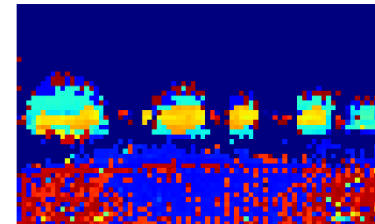
$$R_{nom} = -2$$



$$R_{nom} = -\infty$$



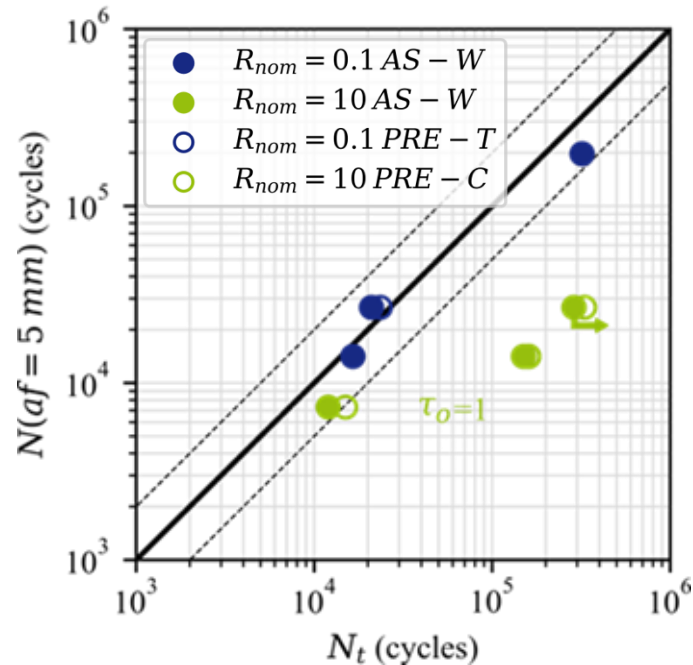
$$R_{nom} = -5$$



# Fatigue crack closure detection

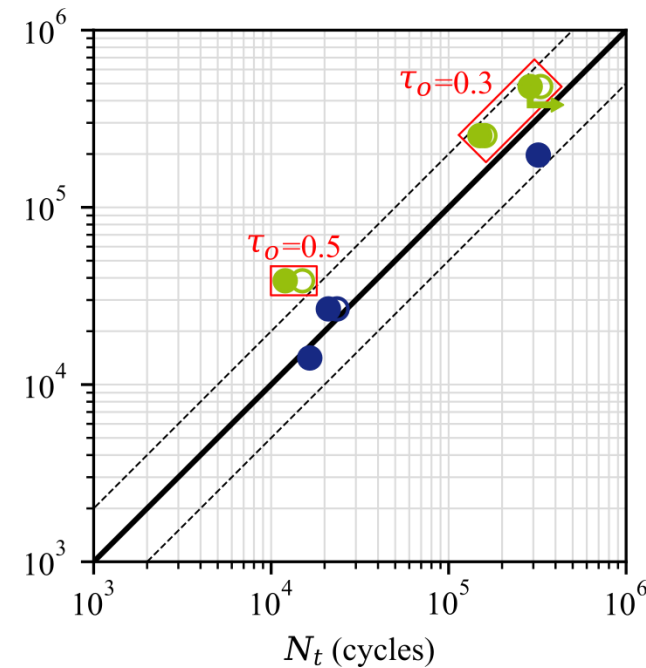
$$N(a = a_f) = \frac{1}{C_p [\Delta \sigma_{eff}]^{m_p}} \int_{a_0}^{a_f} \frac{1}{(F(a) \sqrt{\pi a})^{m_p}} da$$

Paris law  
determined  
via crack  
growth  
monitoring

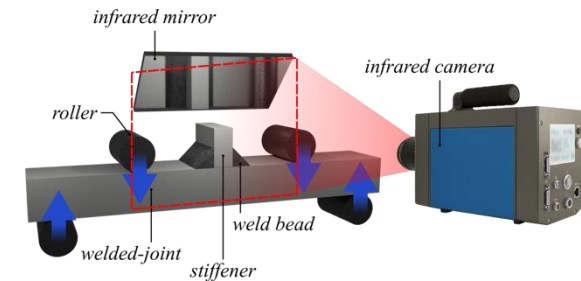


Without crack closure

$$\Delta \sigma_{eff} = \begin{cases} \Delta \sigma_{nom} & \text{if } R_{nom} \in [0; 1[ \\ \tau_o \times \Delta \sigma_{nom} & \text{if not} \end{cases}$$



With crack closure



## Colleagues

Dr. Bercelli, Pr. Calloch, Pr. Doudard, D. Le Bihan, Pr. Marco

## Industrial partners

Vibracoustic, Naval Group, Safran

## InfraTec

Thanks to InfraTec for the organization of this event (Dr. S-A Wode, R. Safina, L.M. Calow).

A special thanks to Dr. S-A Wode for the great collaboration and the exchanges over the years.

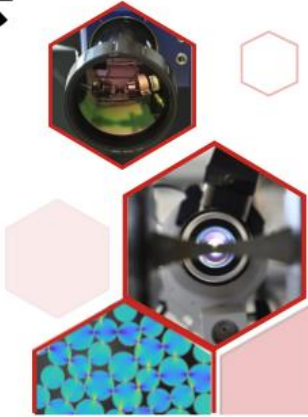
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- A. Mion, Comportement dissipatif à basse et à très haute fréquence de sollicitation et à haute température des superalliages à base de nickel. PhD thesis ENSTA (2025) : <https://univ-brest.hal.science/tel-05455947v1>
- P. Lepitre. Étude de l'influence de l'intégrité de surface et d'un revêtement sur les propriétés en fatigue à grand nombre de cycles de l'acier 300M par mesures thermométriques sous chargement cycliques. PhD thesis ENSTA (2024) : <https://theses.hal.science/tel-05050891>
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# PhotoMechanics Conference

Paris

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