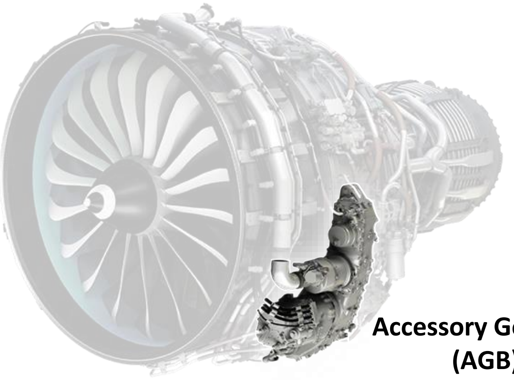
HCF AND VHCF OF CARBURIZED STEELS: FROM COMPETING CRACKING MECHANISMS TO LIFETIME VARIABILITY

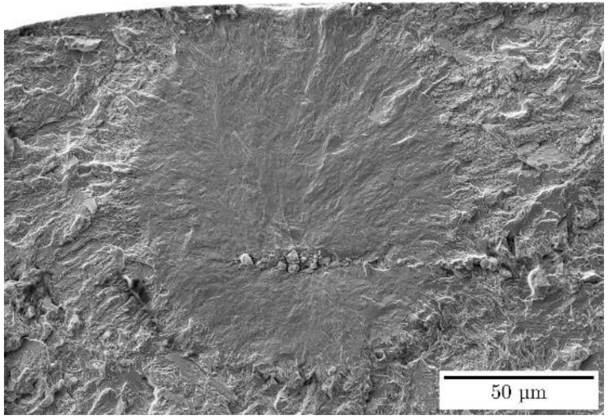


Accessory Gear Box (AGB)

60 YEARS OF RUMUL

NEUHAUSEN - SWITZERLAND

SEPTEMBER 18TH TO 19TH -2024



Vincent ARGOUD[1,2], Franck MOREL[1], Etienne PESSARD[1], Daniel BELLETT[1], Simon THIBAULT[2], Stéphane GOURDIN[2]

[1]*LAMPA, Arts et Métiers Angers, 2 Bd du Ronceray, 49035 Angers, France*

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Laboratoire Angevin de Mécanique, Procédés et innovAtion

ARTS ET MÉTIERS **IN NUMBERS**

KEY FIGURES

1780

Creation of the School by the Duke of Rochefoucauld-Liancourt

11
SITES
located all over France dedicated to Teaching & Research

420
PhD STUDENTS
at our Doctoral School "Sciences des Métiers de l'Ingénieur"

1
BACHELOR OF TECHNOLOGY

6000
STUDENTS
all programs included

15
LABORATORIES
and research teams

11
ENGINEERING PROGRAMS
1 broad-based 10 specialized

1100
PERSONNEL
Teachers, Technicians & Administrative Staff

7 MILLIONS €
income

+20
RESEARCH MASTERS

20 MILLIONS €
income generated by industry contracts

2000
CONTINUING EDUCATION
auditors

17
EXECUTIVE MASTER PROGRAMS

"Diplôme d'ingénieur" degree equivalent to Master's degree of industrial and mechanical engineering

ARTS ET MÉTIERS **RESEARCH** IS CONDUCTED IN **20 DIFFERENT DOMAINS**

- Mechanical Engineering
- Biomechanical health/design
- Fluid Dynamics
- Thermal Energy
- Material Analysis
- Analysis & Implementation of Polymers
- Laser Processes
- Additive Manufacturing
- Electrical Engineering
- Collaborative Robotics
- Tribology & Surface Treatment
- Forging and Forming of Materials
- Casting
- Machining
- Virtual Reality
- Wood Analysis and Manufacturing
- Construction and Building Materials
- Numerical Engineering
- Design (Innovation/ Production Systems)

FULL LIFE CYCLE

Design and Innovation → Industrialization Processes → Maintenance Durability → Recycling

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1 INSTITUTION WITH
8 CAMPUSES AND **3 SATELLITE LOCATIONS**
15 LABORATORIES CLOSE TO LOCAL ECONOMIC PLAYERS

- 350 researchers
- Enhanced by our partnerships with local universities and institutions
- A strong national presence

LAMPA SAFRAN Arts et Métiers

ANGERS CITY

Pleasant climate and Art de vivre

400 000 inhabitants (3rd most populous city in the west)

1h30 from Paris by TGV

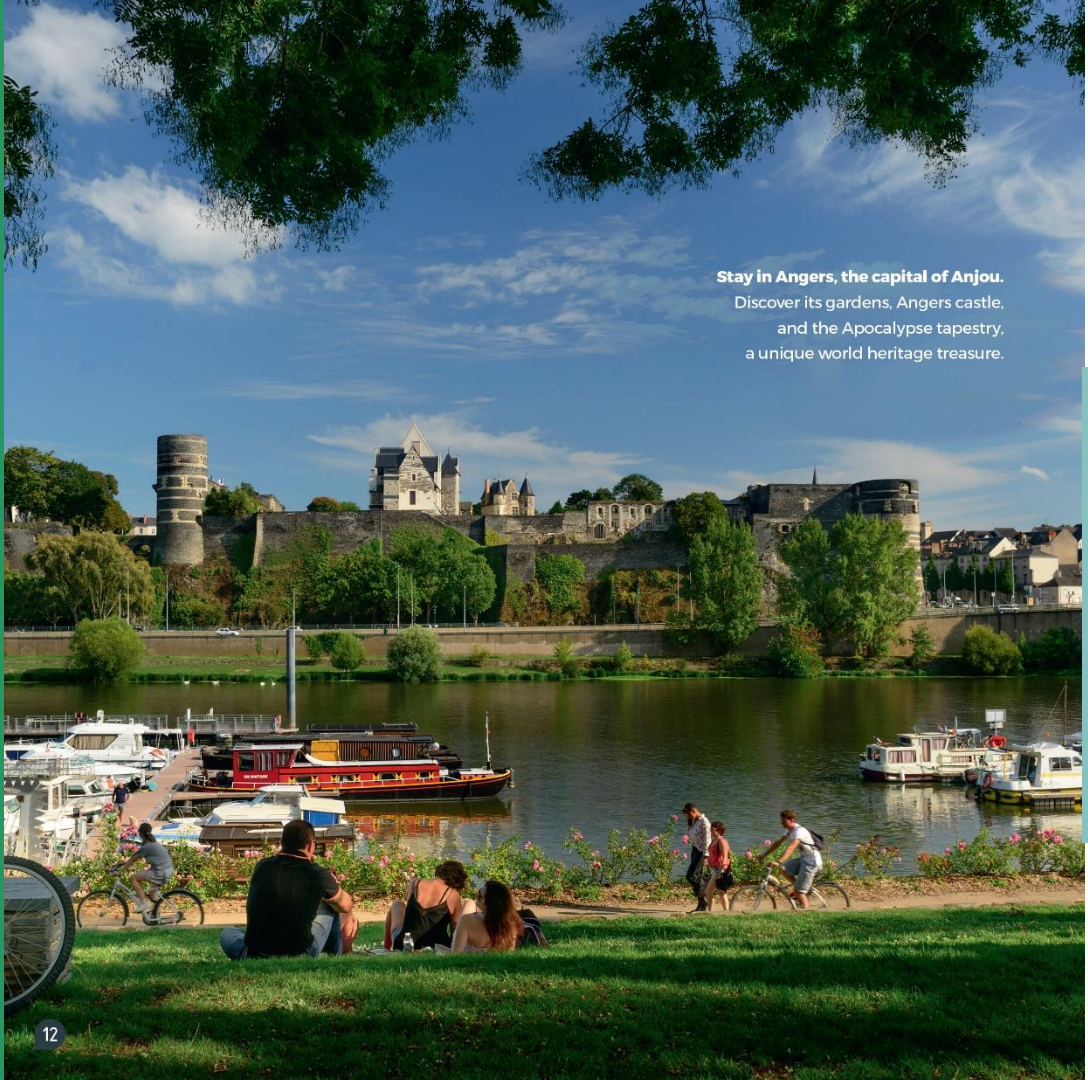
1h15 from the coast

3rd largest wine region

45 000 students

Région
PAYS DE LA LOIRE

5th economic region in France
*Population: **3,700,000***
***160,000** students*



No1 FOR QUALITY OF LIFE

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LAMPA

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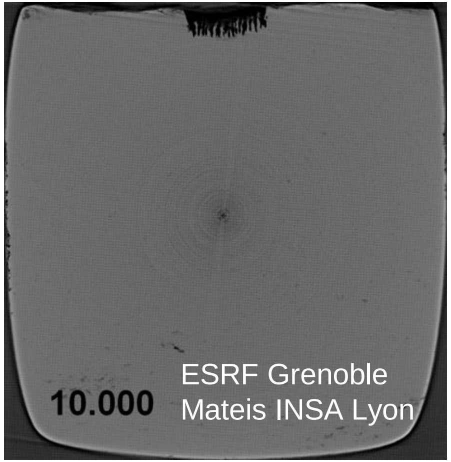
FATIGUE

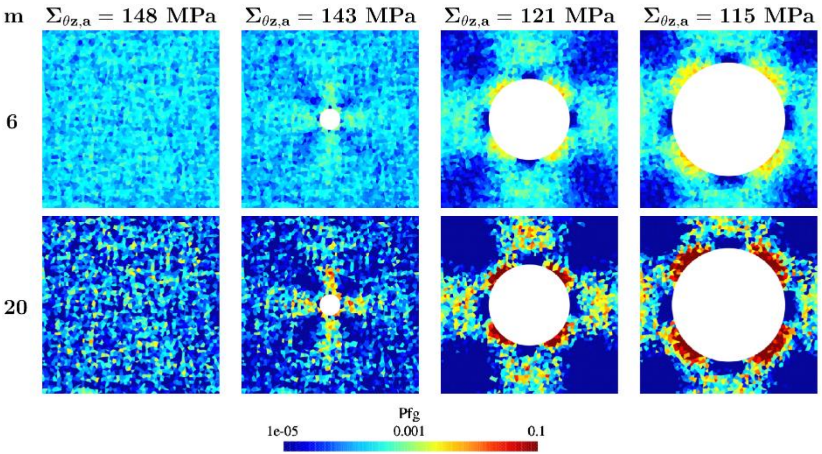
R&D SKILLS

Simulation
Characterization
Testing

Fatigue of materials and structures

- Effect of manufacturing process (ColdWorking, Casting, machining, Additive manufacturing, welding …) on fatigue strength
- Microstructure-sensitive modelling of fatigue damage
- Fatigue under multiaxial and variable amplitude loading
- Gradient and size effect
- Defects
- Fatigue of Bio-composite (flax, hemp fibers, thermoplastic matrix)





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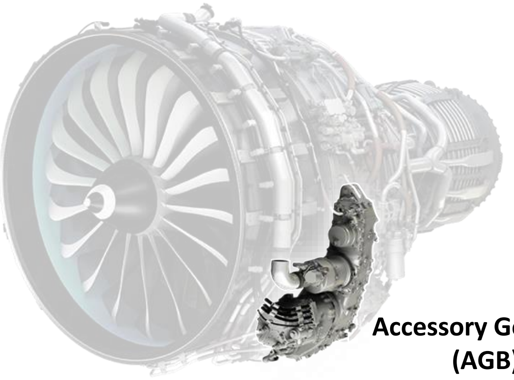

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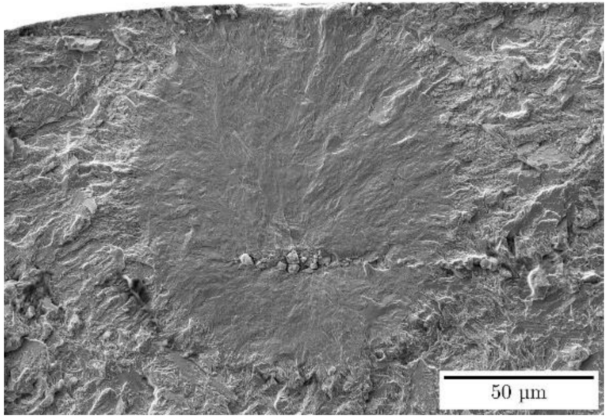

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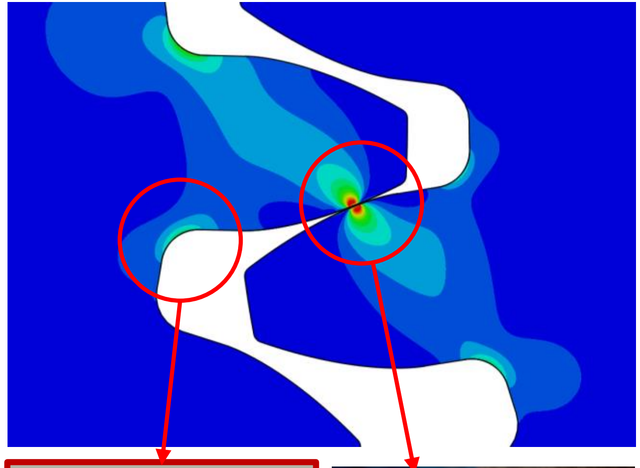
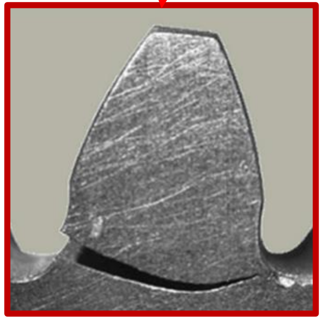
SAFRAN

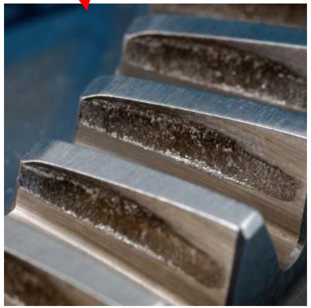
Arts et Métiers Institute of Technology

1. Introduction

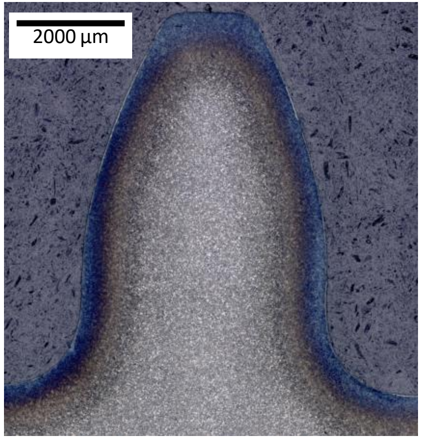
Loading and failure modes in gears







- Most common fatigue failure modes in gears : rolling-contact fatigue and **tooth root bending fatigue** [ASM Handbook Vol. 11]
- VHCF (10^7 cycles in a few hours)

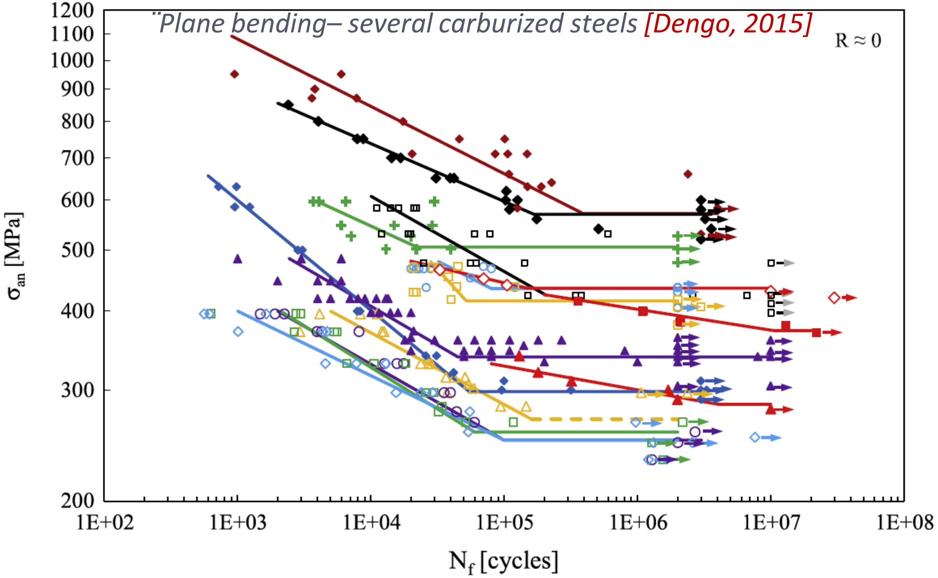


- Stress is concentrated close to the surface → ThermoChemical treatments are applied to enhance mechanical properties
- TC create a **carbon (carburizing)** or nitrogen (nitriding) concentration gradient between the surface and the core material
- Microstructure/hardness gradient and residual stresses enhance wear resistance and fatigue strength

1. Introduction

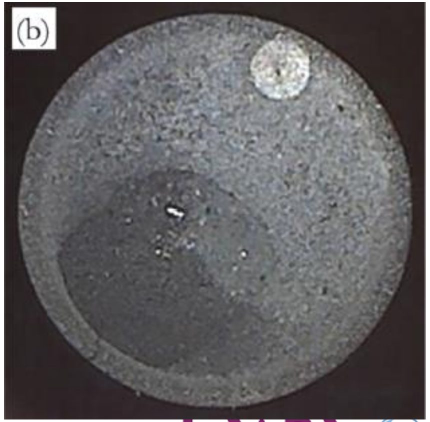
Literature data

1. Various fatigue tests (Single tooth Bending Fatigue on gears, Rotating bending, push/pull loading, plane bending)
→ different crack initiation mechanisms
2. Strong effect of steel/Thermochemical
3. Very few studies $N > 10^7$



Scientific challenges

1. Be reprentative of in service cracking mechanisms and fatigue strength
2. Characterize Fatigue crack initiation and growth mechanisms
   - Steel/TC: Hardness, residual stresses, microstructure
   - Stress gradient due to loading
3. Fatigue life prediction for case hardened steels
   - scatter

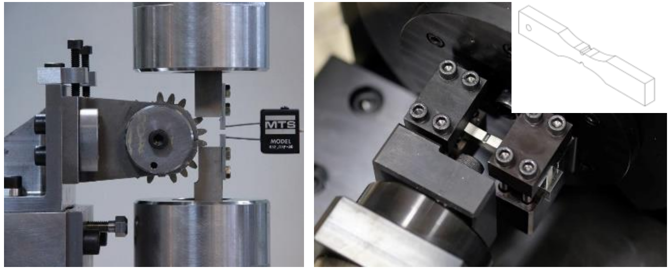


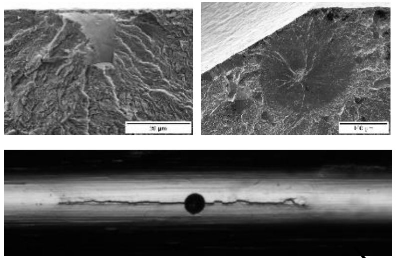
Rotating bending – smooth specimens
Carburized steel [Jo, 2!016]

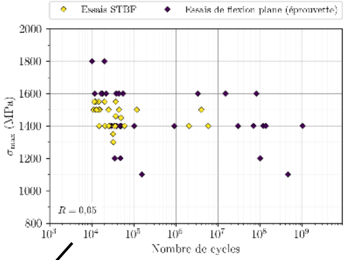
1. Introduction

Scientific approach

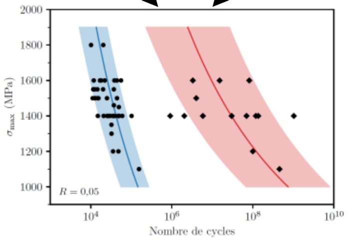
- Experimental investigation
  - Fatigue strength
    - 3 carburized steels (**16NiCrMo13,** *M50Nil, Ferrium C64*)
    - 10^4 to 10^9 cycles
    - STBF and bending notched specimen
  - Damage mechanisms
    - Initiation
    - Growth kinetic







- Modelling approach
  - Probabilistic approach to model the S-N curves
    - Explain macroscopic response From crack initiation and growth mechanisms



Presentation outline

1. Introduction

2. Experimental conditions : STBF and Plane bending for carburized 16NiCrMo13

3. Fatigue strength and crack initiation mechanisms

4. Crack growth and Bimodal fatigue behaviour

5. Conclusion et perspectives

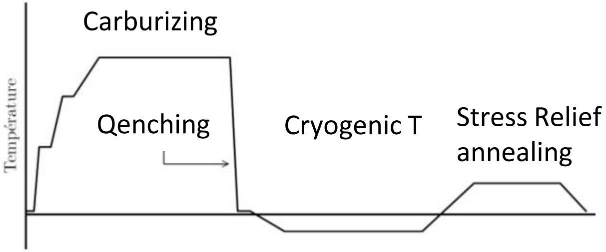
2. Material and experimental conditions

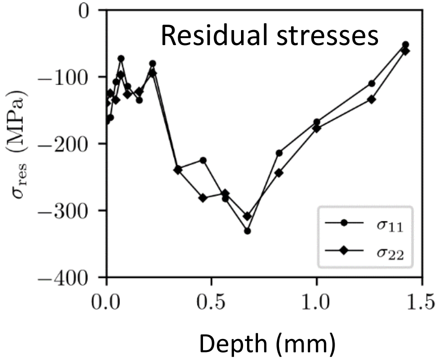
Carburized 16NiCrMo13 steel

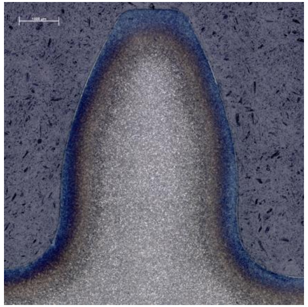
wt %	Fe	C	Ni	Cr	Mn	Mo	Si	Cu	Al	P	S
Min.	Base	0,12	3,00	0,90	0,30	0,15	0,15	–	–	–	–
Max.	Base	0,17	3,50	1,15	0,60	0,30	0,35	0,35	0,05	0,015	0,008

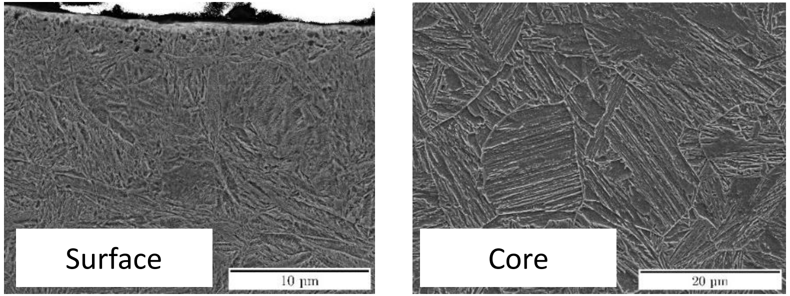
Time to achieve 1mm depth	Hardness	σ_Y (core)	σ_{UTS} (core)	Tempering temp.
< 5h	Surf. : ~ 720 HV Core : ~ 400 HV	~ 1050 MPa	~ 1350 MPa	~ 200 °C

Low pressure carburizing with C3H8 in ALD furnace at 920 °C followed by gas quenching , cryogenic treatment, and stress relief.

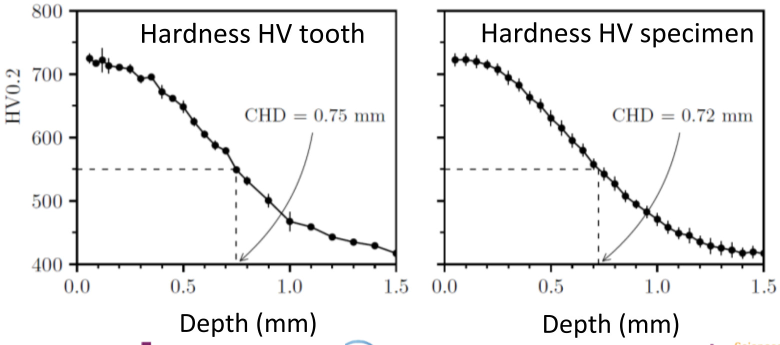




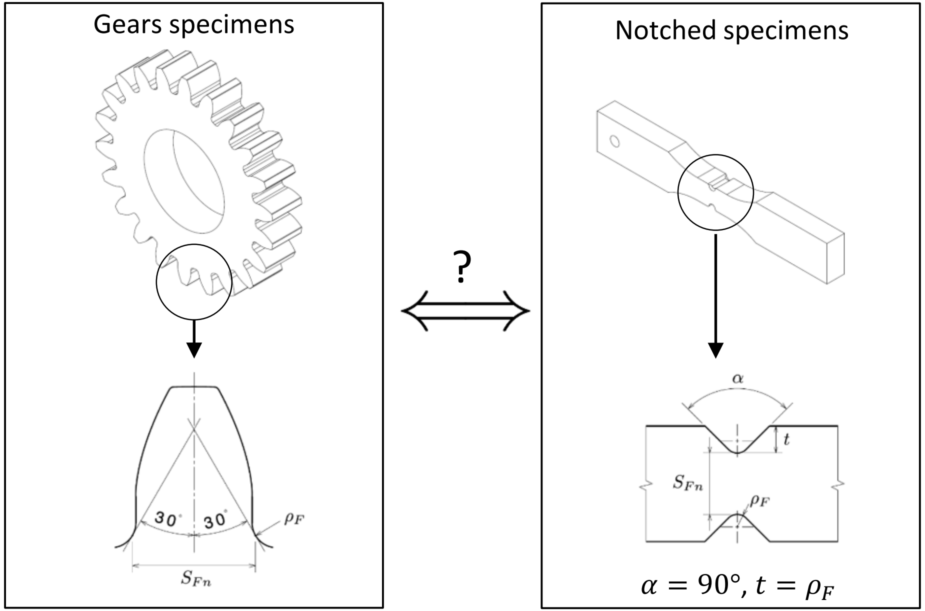


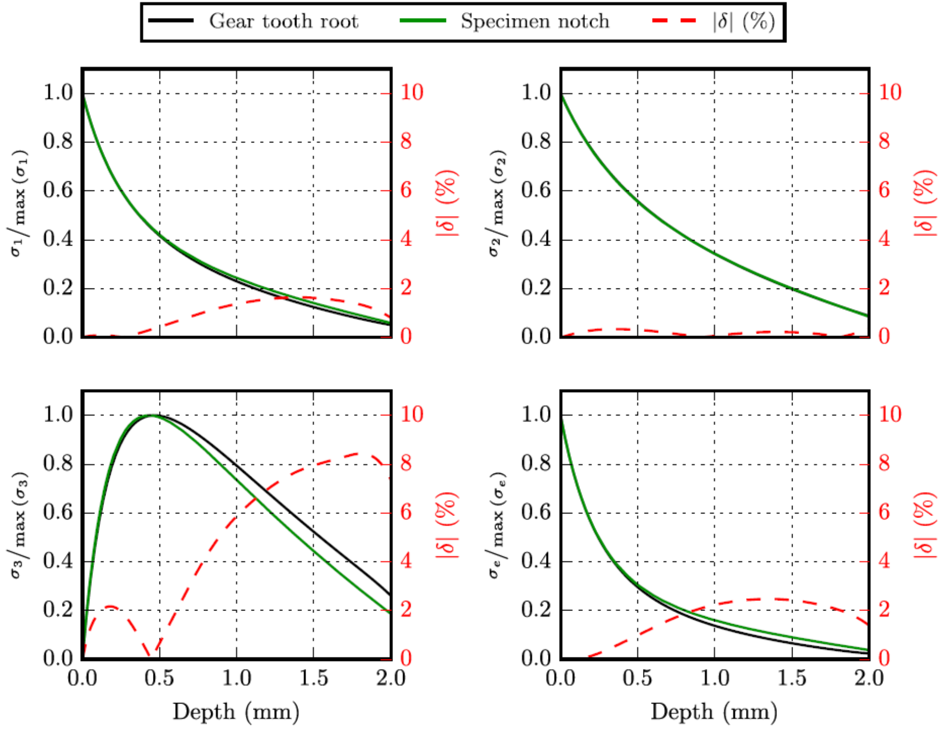


Martensite + retained Austenite (~ 6-8 % at surface)



Specimens and test set-ups





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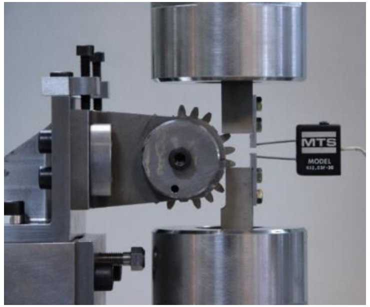
Specimens and test set-ups

Single Tooth Bending Fatigue (STBF)

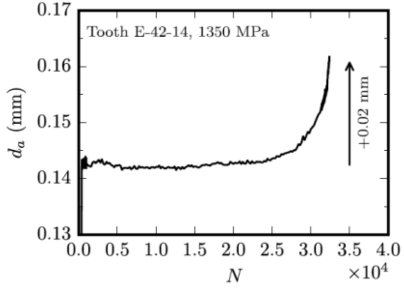
Specific test bench adapted to a MTS servo-hydraulic fatigue machine



> **Conditions :**
- 22 teeth gears, m=2,54
- Frequency = 40 Hz
- R = 0,05

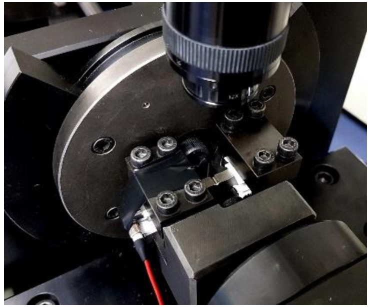
> **Measurements :**
- Anvil displacement amplitude
- Stereo-correlation

Crack initiation criterion



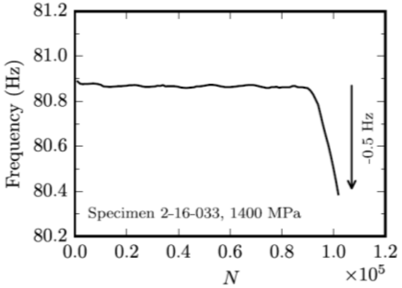
Plane Bending Fatigue (PBF)

RUMUL Cracktronic resonant fatigue testing machine



> **Conditions :**
- Notched specimens
- Frequency = 80 Hz
- R = 0,05

> **Measurements :**
- Frequency drop
- Acoustic emission
- Silicon rubber replication



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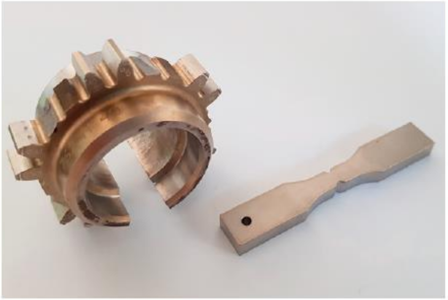
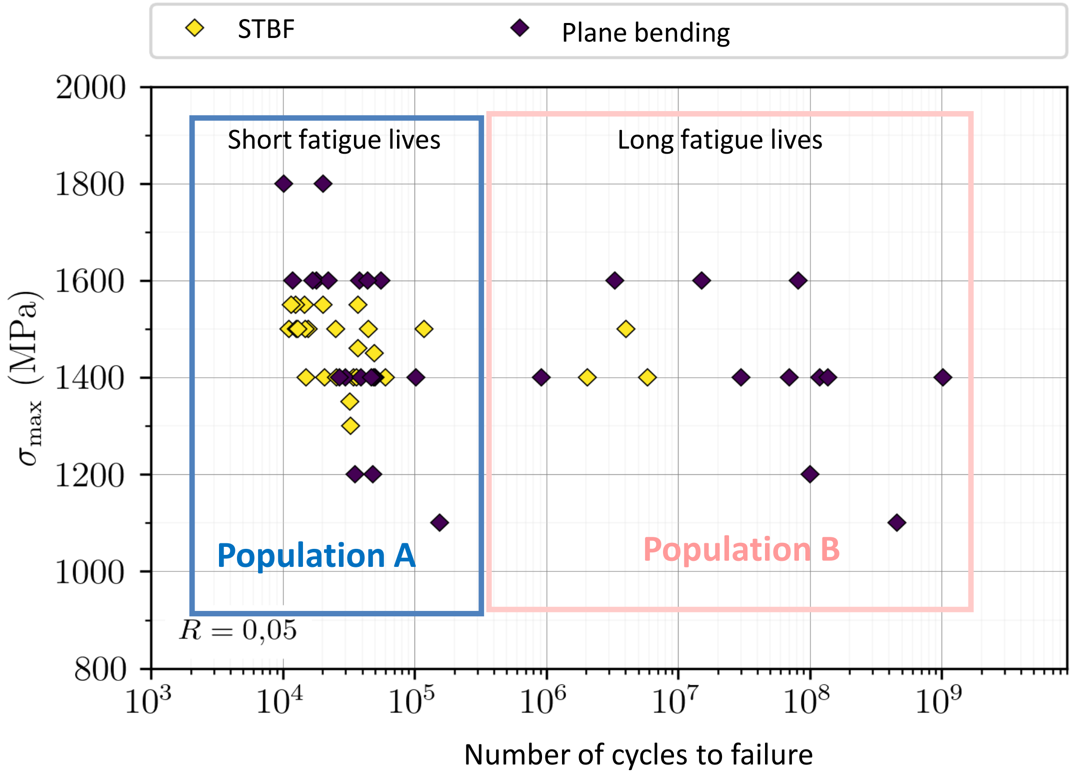
5. Conclusion et perspectives



Carburized 16NiCrMo13 – Fatigue strength

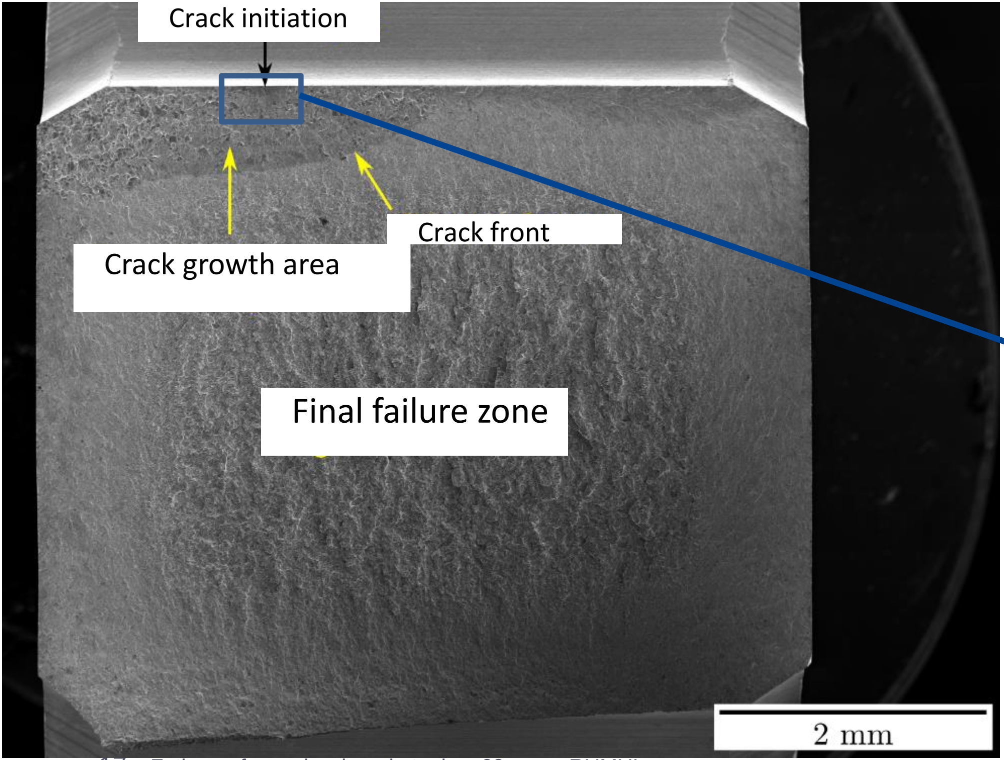
- **STBF + plane bending (carburized 16NiCrMo13)**

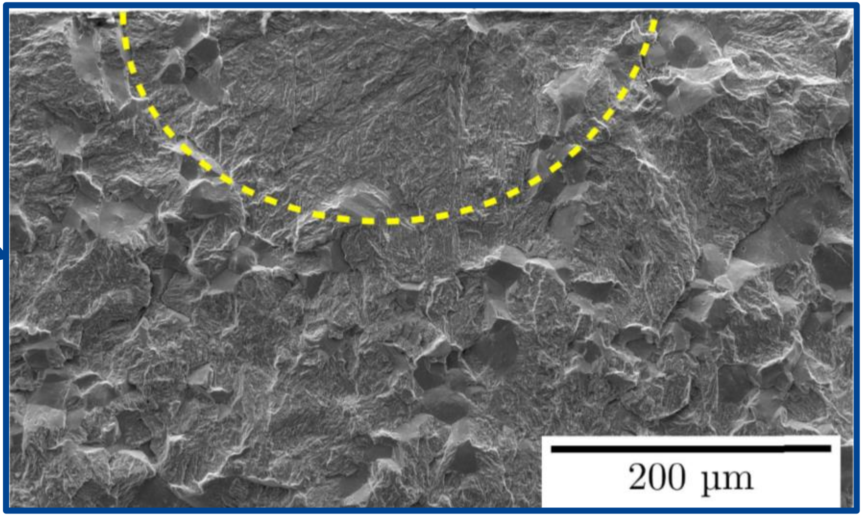
1. STBF strength (27) = Notched plane bending specimen strength (38)
2. Huge scatter
3. 2 populations
   - Bimodal behaviour ?
   - Initiation/Propagation ?



Carburized 16NiCrMo13 – Fracture surface

- **STBF + plane bending (carburized 16NiCrMo13)**





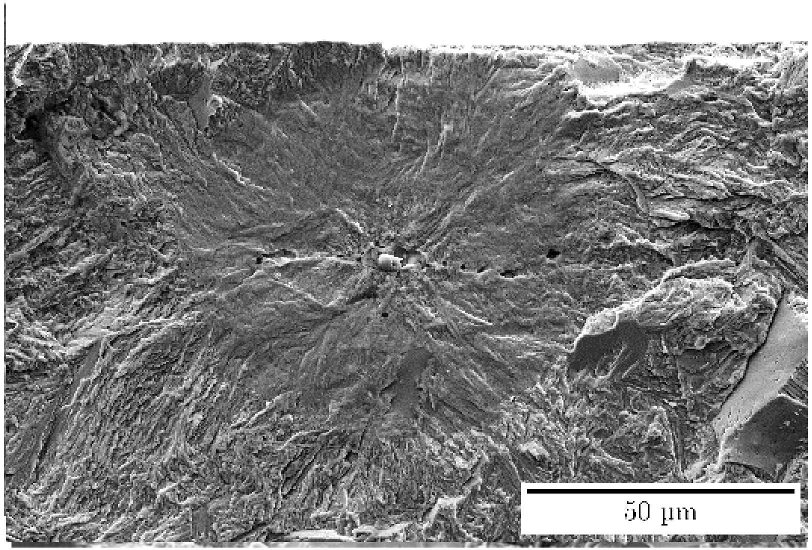
N_f=914 273 cycles

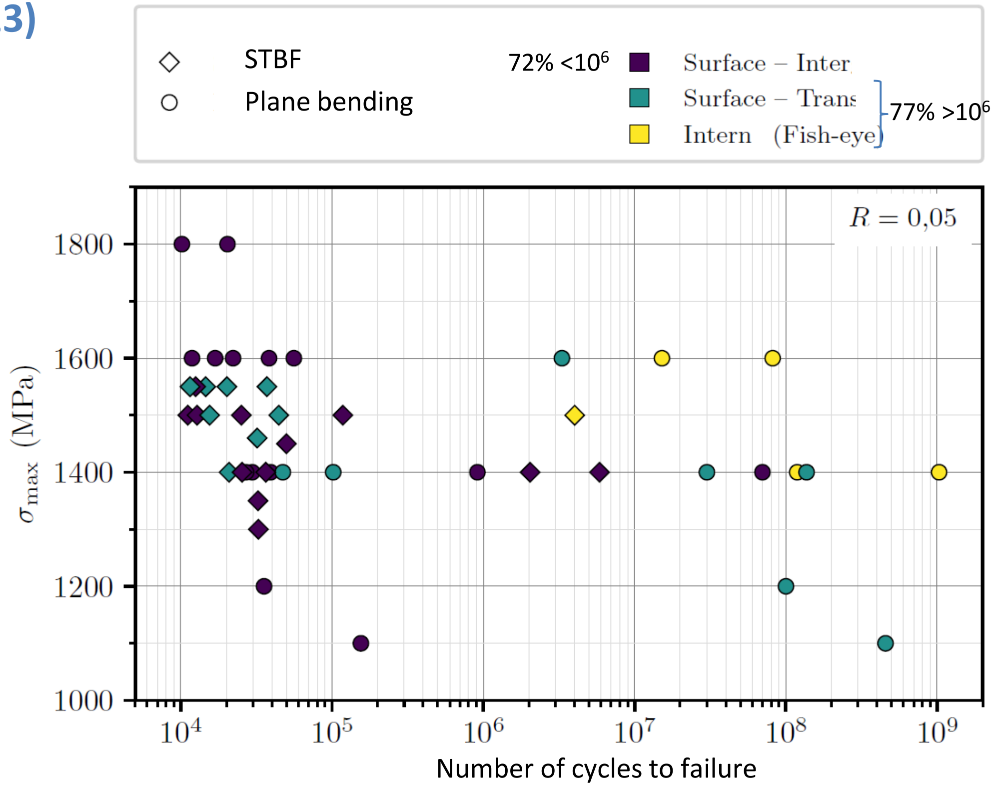
σ_{max}=1400 MPa

Carburized 16NiCrMo13 – Crack initiation mechanisms

▪ STBF + plane bending (carburized 16NiCrMo13)

- 3 different crack initiation mechanisms
- **Mechanisms correlated to fatigue life**





Things worth remembering

1. Very good correlation between the fatigue behaviours of gear specimens and notched specimens

2. 16NiCrMo13 : Strong fatigue life variability for a given stress level (competition between intergranular, transgranular, internal cracking mechnisms) 10^4 to 10^9 cycles

3. 3 carburized steels (16NiCrMo13 : 65+59 tests, M50Nil : 120 tests, Ferrium C64 : 22 tests) + 2 load ratios (16NiCrMo13 R=0.1: 65 tests, R=-1: 59 tests) →similar bimodal response

4. Complement 1 : Effect of residual stresses ?
5. Complement 2 : Fatigue bimodal behaviour unique ?

6. Propagation phase? Bimodal modelling?

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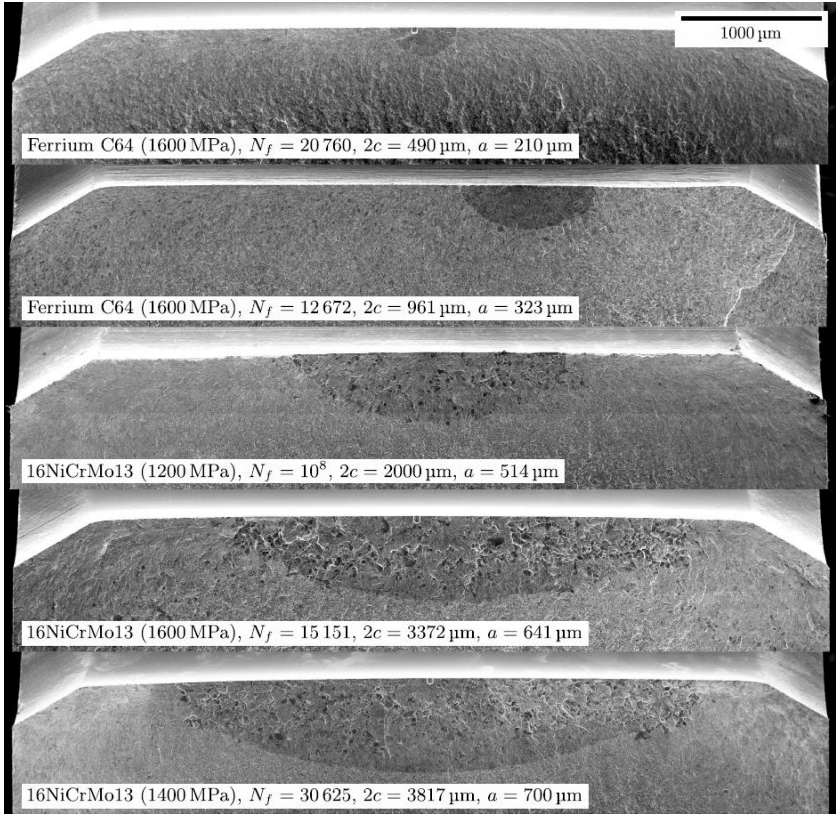
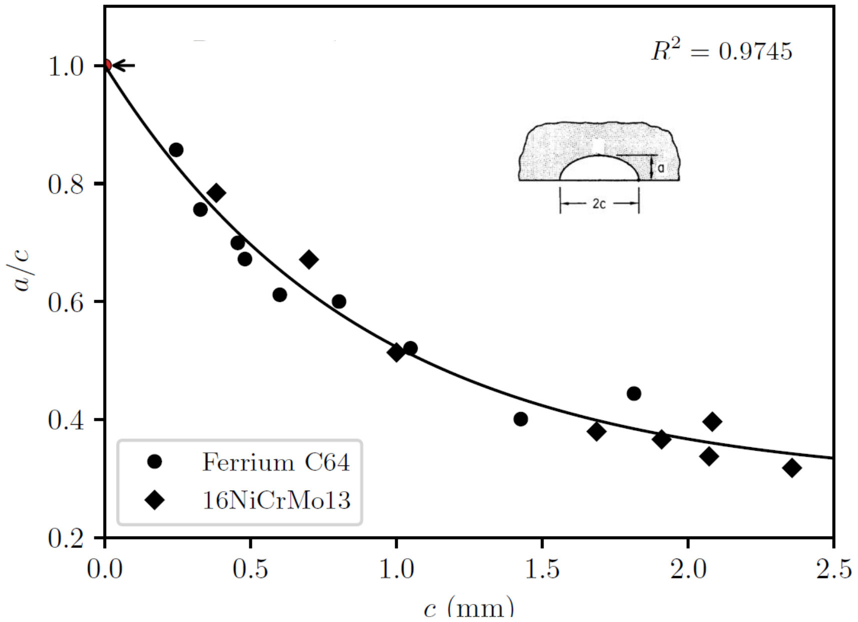
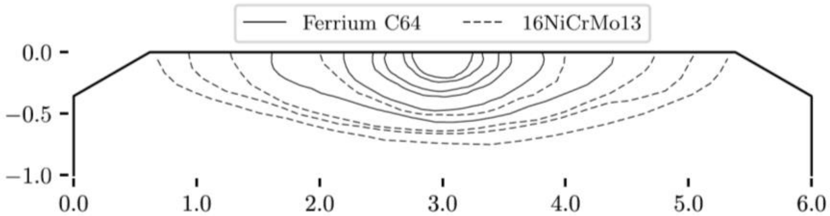
Crack aspect ratio a/c

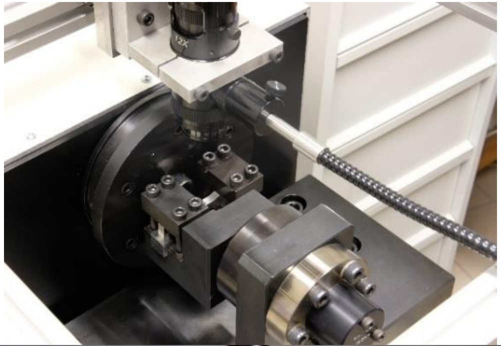


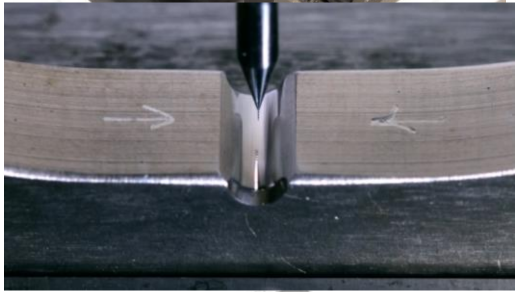


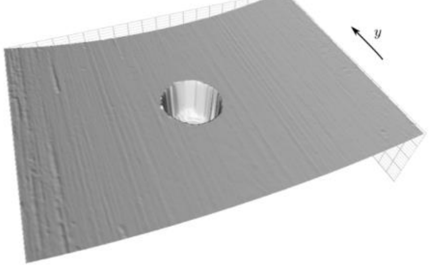


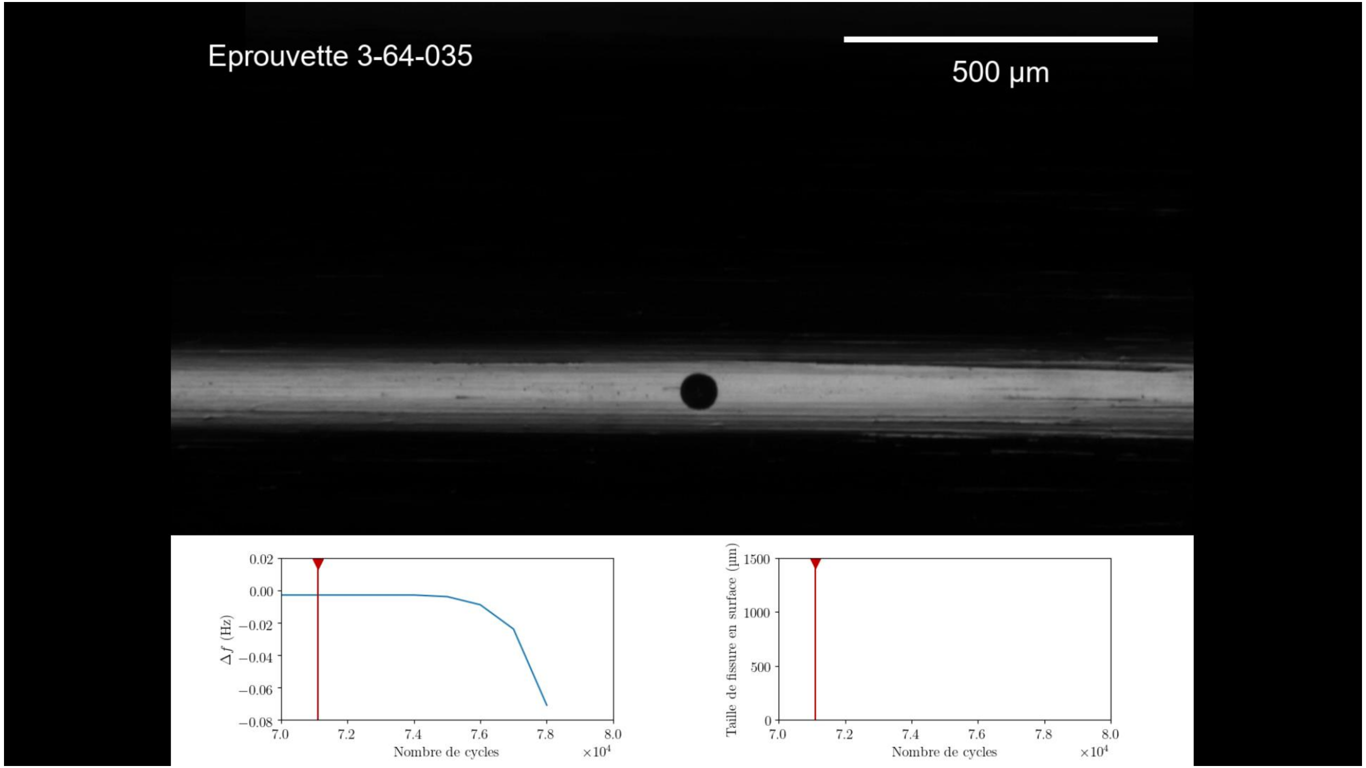
4. Crack growth and bimodal behavior

Crack growth from artificial defects







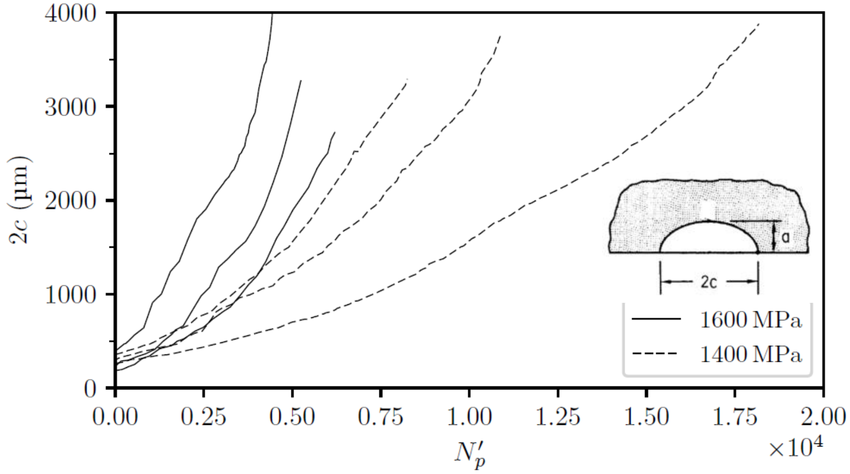


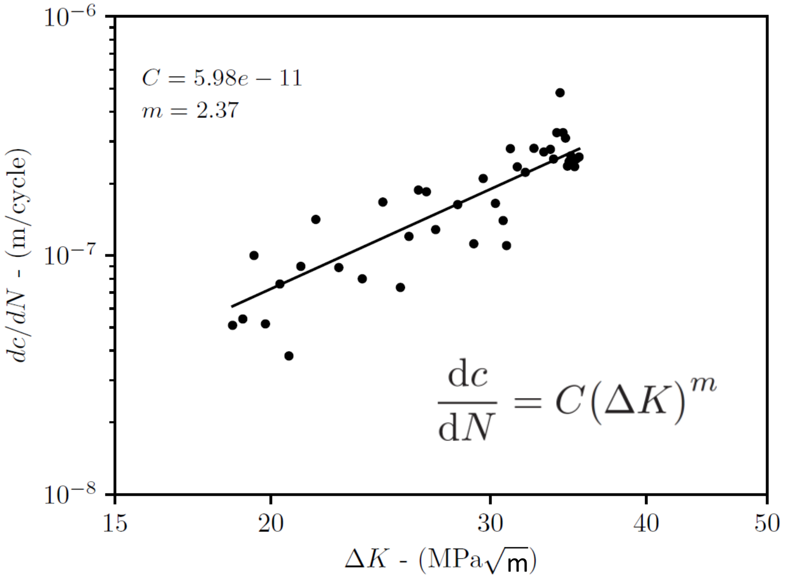
4. Crack growth and bimodal behavior

Paris Law

Carburized 16NiCrMo13

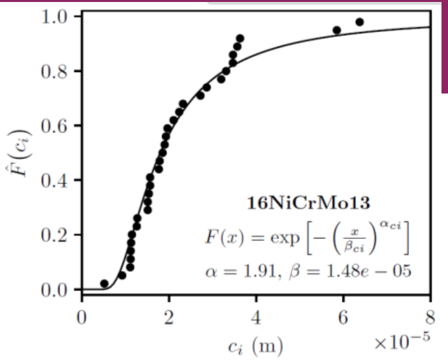
- Weight functions (semi-elliptical surface cracks) [Shen et Glinka, 1991]
- Stress gradient, Residual stresses, c/a=f(c)

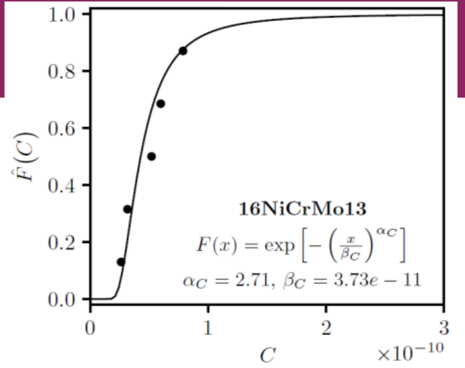




Paris law identification (C,m)

4. Crack growth and bimodal behavior



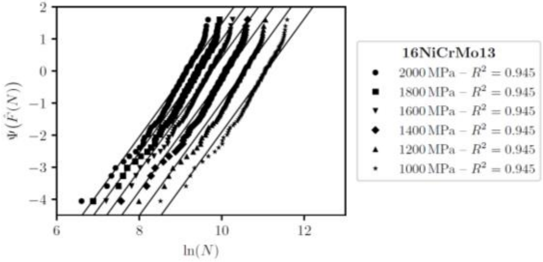


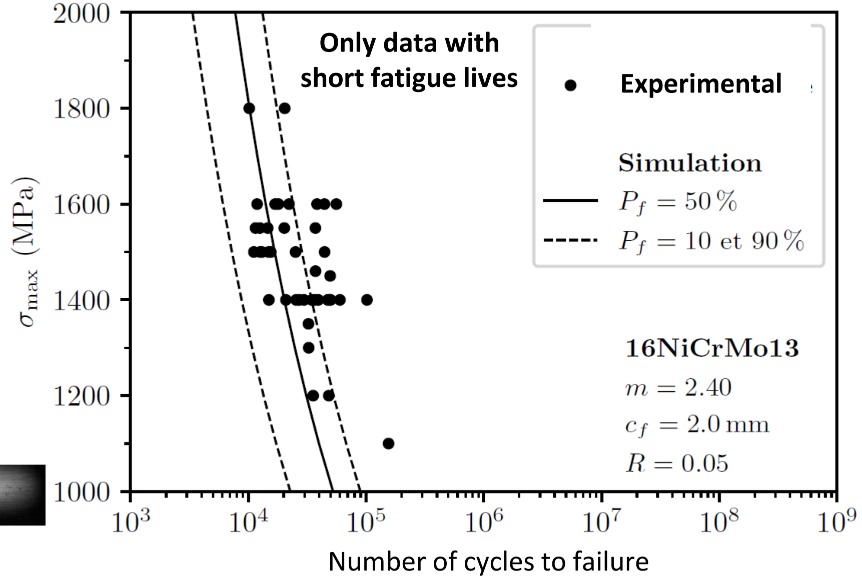
Fatigue life propagation distribution

- Probabilistic approach [Ciavarella, 2018]
  - Initial crack size distribution c_i (Fréchet)
  - Paris Law paramater C (Fréchet)

- Fatigue life (Monte-Carlo)
  1. 100 couples C and c_i
  2. Calculation of N_p

$$N_p = \frac{1}{C} \int_{c_i}^{c_f} (\Delta K(c))^{-m} \mathrm{d}c.$$



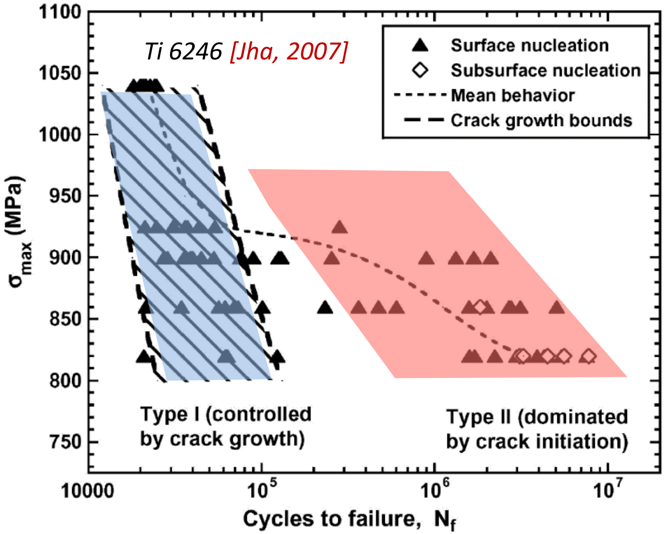


- Good correlation with experimental data
- Population of data with short lives → crack growth controlled

4. Crack growth and bimodal behavior

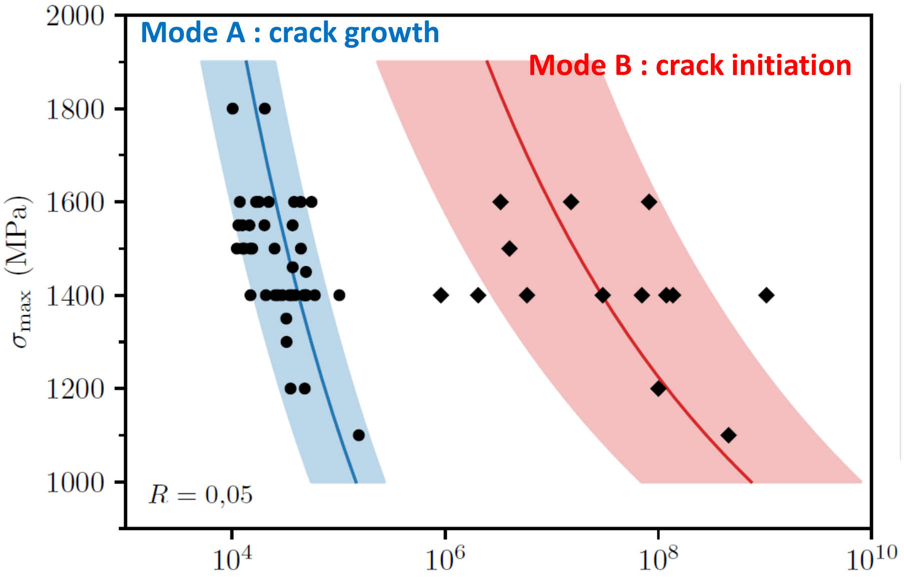
Bimodal behavior

- Already observed for other alloys



Other examples *: steel SUJ2 [Sakai, 2010], superalloys René 95 [Cashman, 2006], aluminium alloy 2024/T3 [Marines, 2003]*

- Carburized 16NiCrMo13



> Clear evidence of a bimodal behaviour

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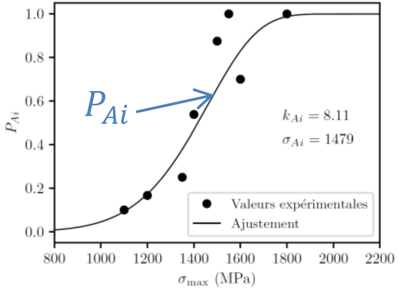
Bimodal behavior probabilistic model (weakest link)

- Main assumptions (3 distributions $P_{Bi}, P_{Ai}, P_{Ap|Ai}$)
  - **Event A** : Short life (Rapid initiation of a crack → **controlled by crack growth**)
  - Probability of rapid initiation depends on the maximum stress level

$$P_A = P_{Ai} P_{Ap|Ai}$$



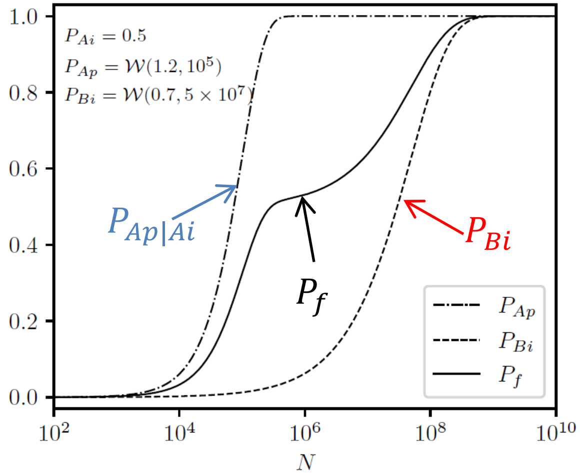
  - **Event B** : Long life (**Intiation phase predominant**)

$$P_B = P_{Bi}$$

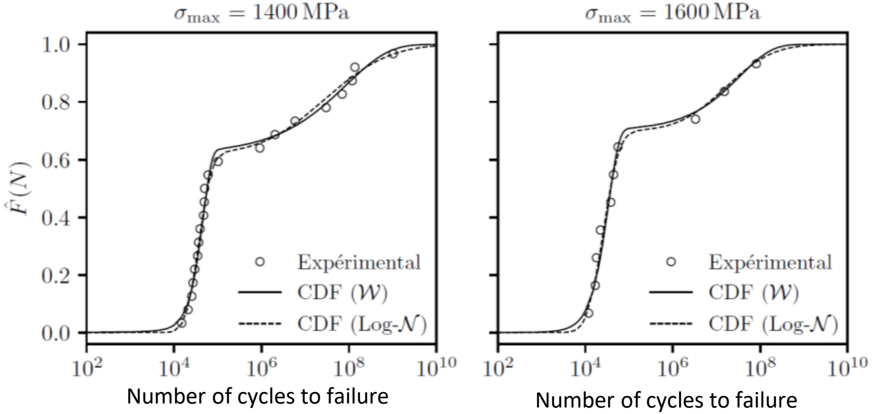
  - **Weakest link concept**

$$P_f = \mathbb{P}(N_f \leq N)$$

$$P_f = P_{Bi} + [1 - P_{Bi}] P_{Ai} P_{Ap|Ai}$$



Carburized 16NiCrMo13



4. Crack growth and bimodal behavior

Bimodal behavior probabilistic model

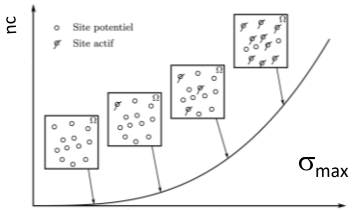
$$P_f = P_{Bi} + [1 - P_{Bi}] P_{Ai} P_{Ap|Ai}$$

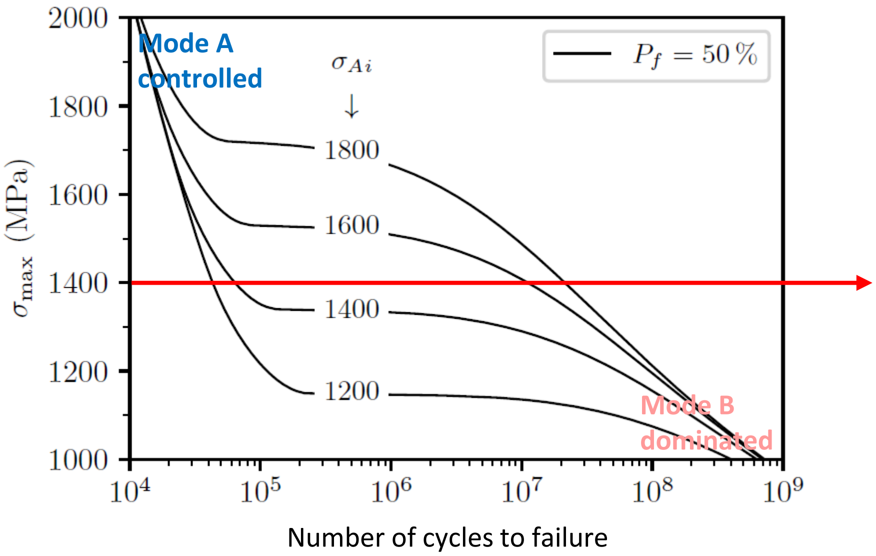
Poisson Point Process :

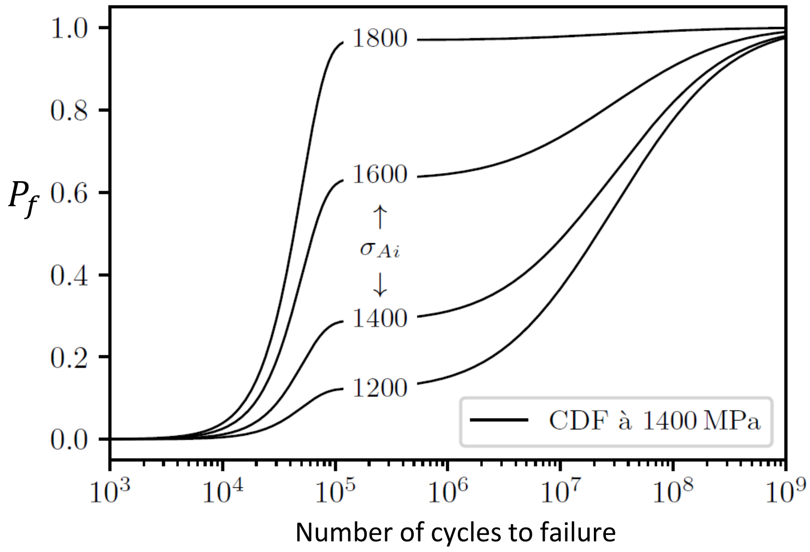
$$P_{n_c}(\Omega, \sigma_{\max}) = \frac{[V_\Omega \lambda_{Ai}]^{n_c}}{n_c!} \exp\left[- V_\Omega \lambda_{Ai} \right]$$

$$P_{Ai}(\sigma_{\max}) = \mathbb{P}(n_c \geq 1)$$

$$P_{Ai}(\sigma_{\max}) = 1 - \exp\left[- \left(\frac{\sigma_{\max}}{\sigma_{Ai}} \right)^{k_{Ai}} \right]$$







> P_{Ai} governs the level of the transition (scale factor) and the scatter (shape factor) around the transition Mode A / Mode B

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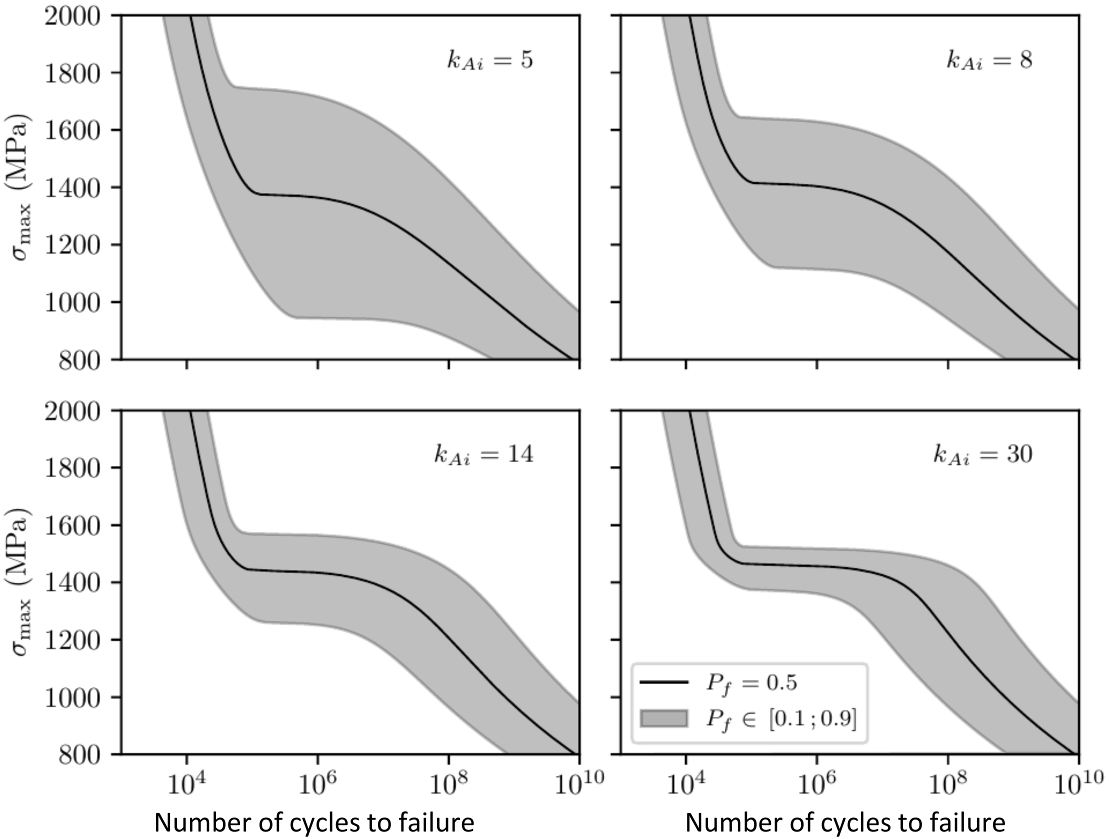
Bimodal behavior probabilistic model

$$P_f = P_{Bi} + [1 - P_{Bi}] P_{Ai} P_{Ap|Ai}$$

$$P_{Ai}(\sigma_{max}) = 1 - \exp\left[-\left(\frac{\sigma_{max}}{\sigma_{Ai}}\right)^{k_{Ai}}\right]$$

- P_{Ai} governs the level of the transition (scale factor) and the scatter (shape factor) around the transition Mode A / Mode B



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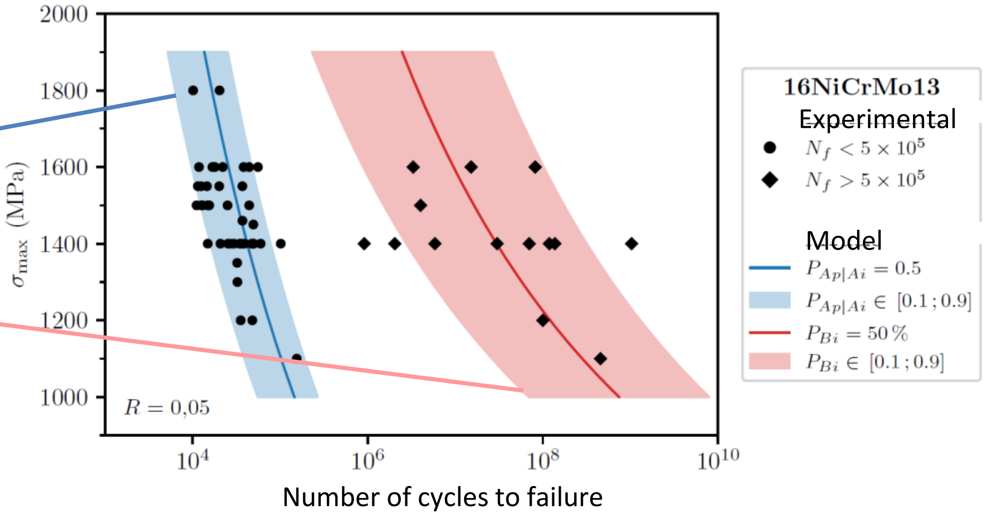
4. Crack growth and bimodal behavior

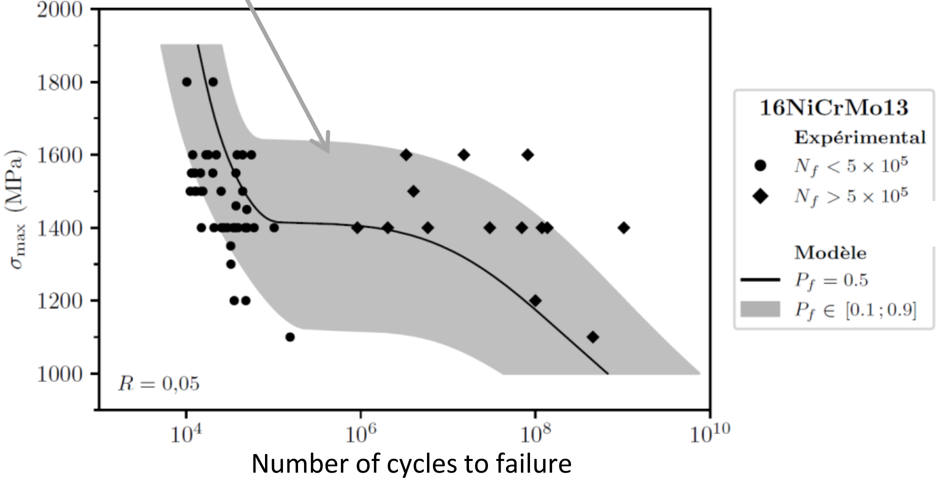
Bimodal behavior probabilistic model

Mode A : controlled by crack growth

$$P_f = P_{Bi} + [1 - P_{Bi}] P_{Ai} P_{Ap|Ai}$$

Mode B : dominated by crack initiation





$$P_f(N, \Delta\sigma, \sigma_{\max}) = P_{Bi}(N, \Delta\sigma) + P_{Ai}(\sigma_{\max}) P_{Ap|Ai}(N, \Delta\sigma)[1 - P_{Bi}(N, \Delta\sigma)].$$

> Huge scatter perfectly reflected

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Presentation outline

1. Introduction

2. Experimental conditions : STBF and Plane bending for carburized 16NiCrMo13

3. Fatigue strength and crack initiation mechanisms

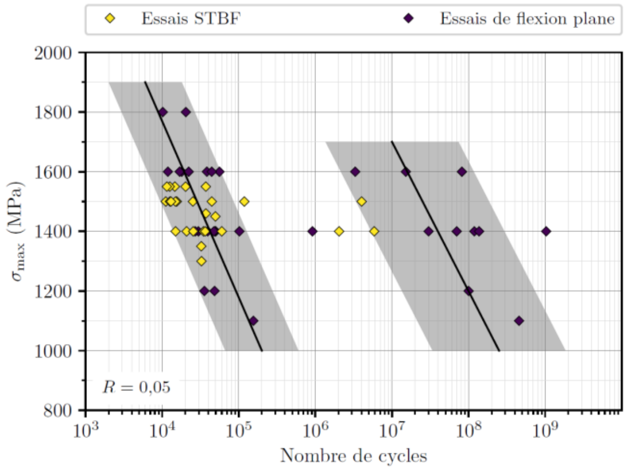
4. Crack growth and Bimodal fatigue behaviour

5. Conclusion et perspectives

5. Conclusions and perspectives

Conclusions

- HCF and VHCF of carburized steels
  - STBF and Notched plane bending specimens : same fatigue strength and crack initiation mechanisms !
- Bimodal behavior
  - Mode A : governed by propagation, Mode B : governed by initiation
  - Ferrium C64, R=-1
  - Probabilistic modelling (weakest link theory) adapted



On going work

- Carburized steel M50 Nil
  - Duplex Carburizing +Nitriding treatment : Hv > 900 : FIB Defect
- Crack growth simulation Abaqus+Zcrack
  - Residual stresses, Microstructure gradient

$$da = \frac{C\,\langle K_{max} - K_{th}\rangle^m}{(1-R)\,\langle K_c - K_{max}\rangle} dN$$

This the end !

There is a crack in everything

…

That is how the light gets in