Introduction of specific residual stress profile in tubular 316L pipe sample

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Experimental methodology for the study of welding residual stresses in nuclear industry components

Laboratory of Structural Integrity and Normalization (LISN)

CEA Paris-Saclay

Club Cast3m 2025

Contents

Introduction - Subject

Objective

Study the influence of welding residual stress (RS) on fatigue crack growth in structure size samples

Difficulties

1. RS influence depends on their value and distribution
2. Hard to control introduced RS profile through welding

Proposition

Develop an experimental rig to introduce predetermined RS profiles through a specific thermo-mechanical cycle

Introduction - Methodology

Objective

Develop an experimental rig to introduce predetermined RS profiles through a specific thermo-mechanical cycle

Steps

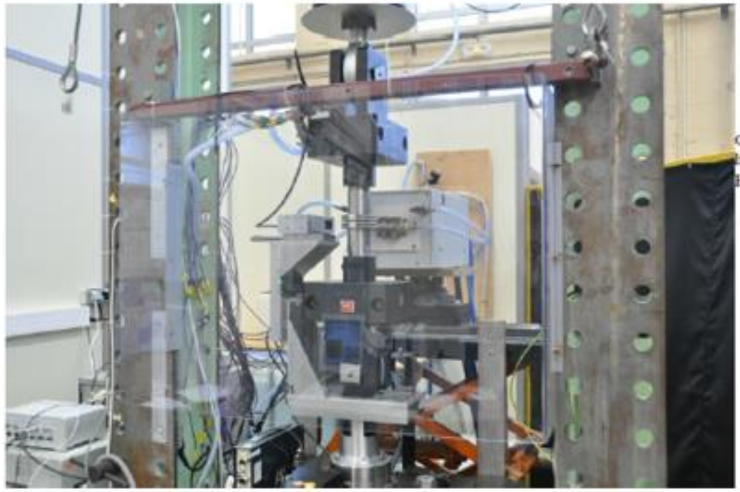
1. Develop a Finite Element Model (FEM) to verify if the proposition satisfies the objective
2. Determine parameters of influence through parametric analysis
3. Numerically fabricate RS profiles to design the experimental rig
4. Design the experimental rig and build it
5. Starts experiment on the rig to calibrate the numerical model on the real thermal behavior
6. Realize the introduction of residual stress in the pipe
7. Measure the residual stress at ILL through neutron diffraction
8. Find out why the predictive FE model isn't predictive…Or is he ?

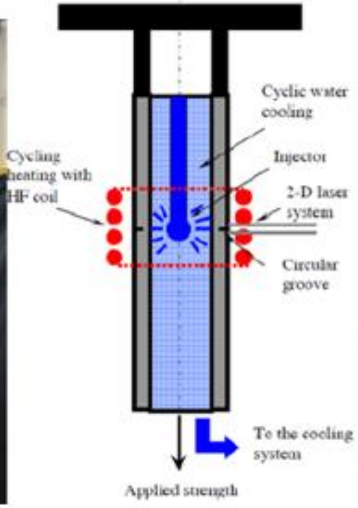
Today

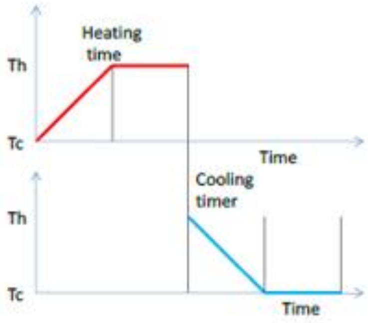
Describe the current state of progress of the project

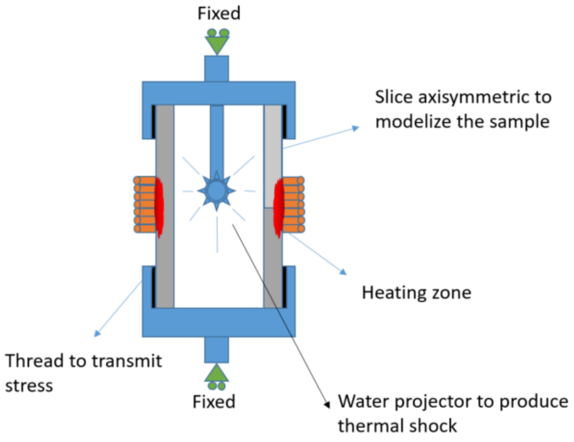
First Step – Finite element model part.1

Previously developed experiment at LISN for the study of PROpagation through THermal Fatigue in 10mm thick pipes (OuterDiam=30mm)









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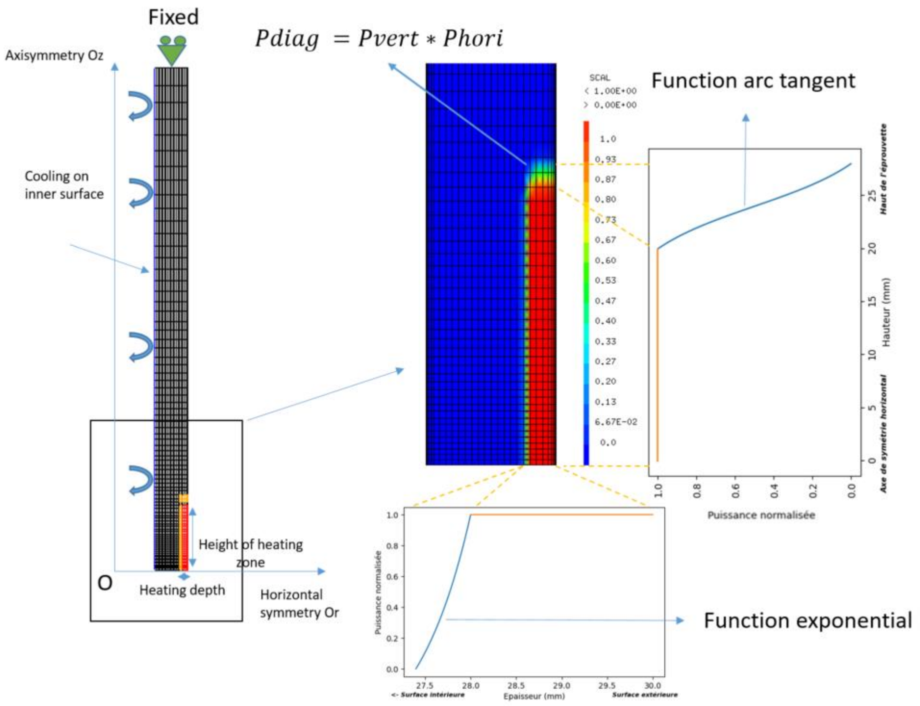


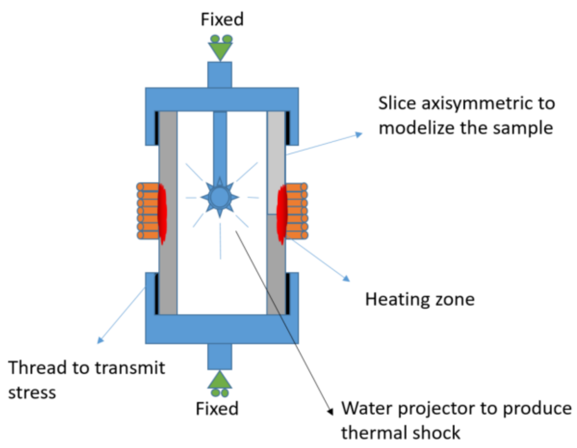
➡

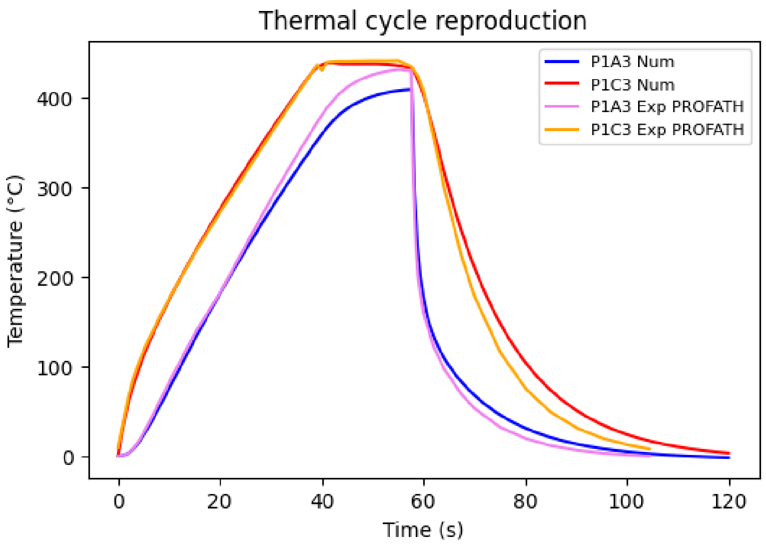
Need of 2 fitting parameters for decreasing heat zone size
=> Using experimental thermocouple data

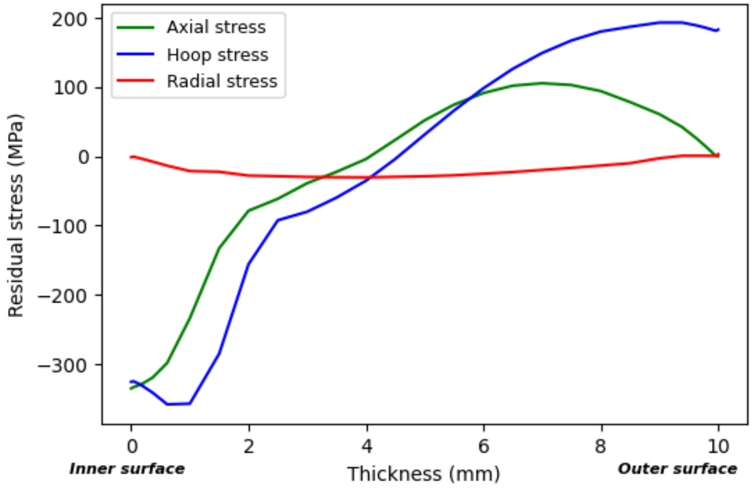
First Step – Finite Element model part.2

Objective

- Determine the thermal parameters using previous experimental data
- Verify the ability to introduce residual stress using PROFATH geometry







Mid-height through thickness residual stress field obtained with PROFATH geometry

PROFATH Allows introduction of residual stress

First Step – Thermal and axial mechanical behaviour

[1] Temperature au temps 0.00000E+00 (0 %)

[2] Contraintes Axiales au temps 0.00000E+00 (0 %) en MPa

Second Step – Parametric analysis

Objective → Determine the most influential experimental parameters influencing residual stress

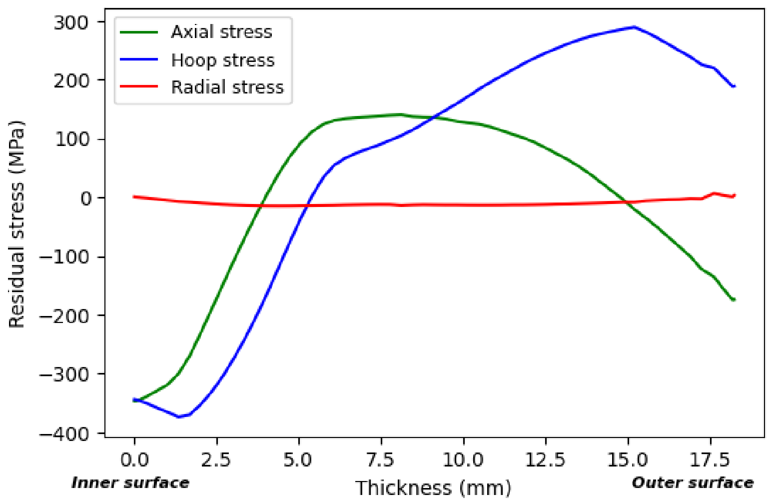
Most influent parameters :

1. Applied stress on the sample
2. Heating zone height (inductor size)
3. Heating cycle
4. Cooling speed (thermal shock violence)

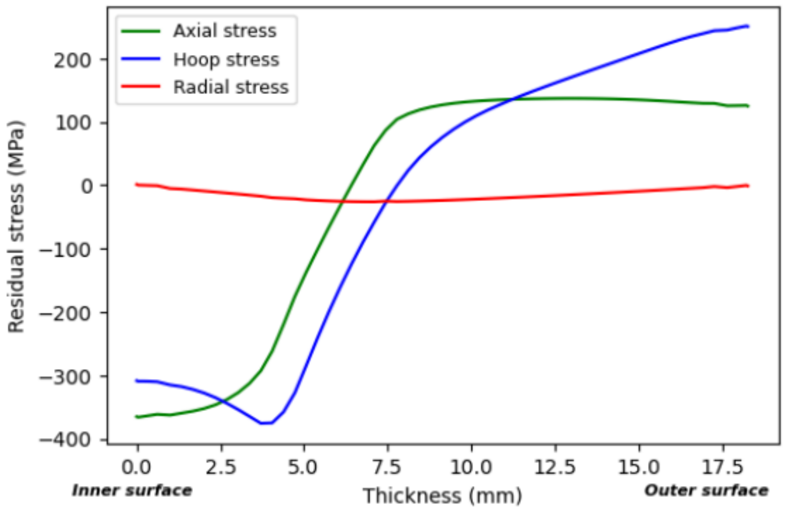
→ 2 different coils for heating in 2 different ways
=> 2 types of residual stress profiles

2 profile chosen on the real geometry :
Pipe 168*17.75*400mm →

20mm height inductor

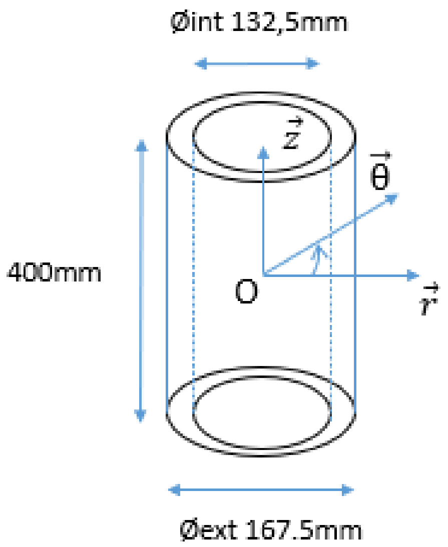


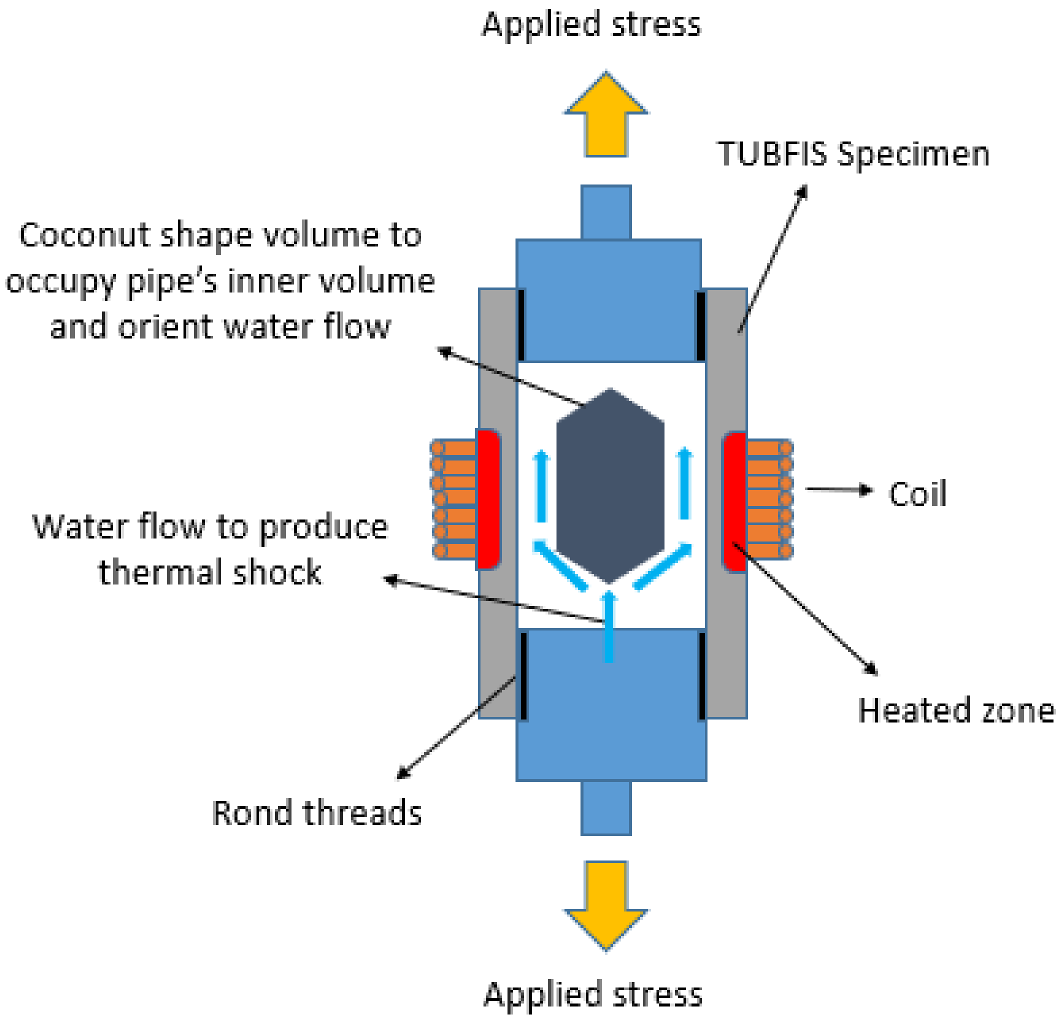
50mm height inductor

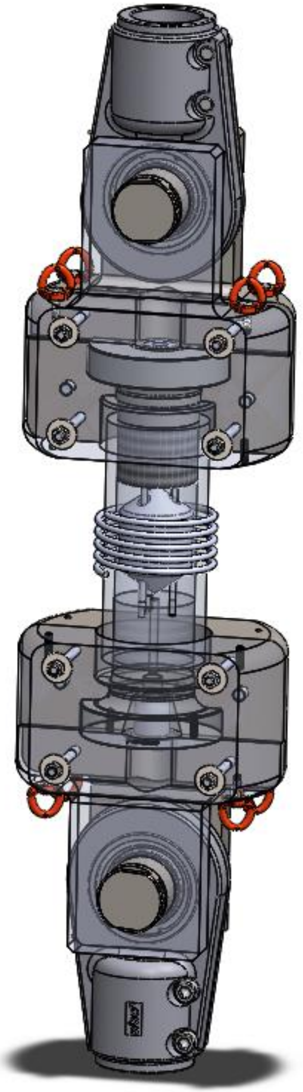


Mid-height through thickness RS fields obtained by FEM

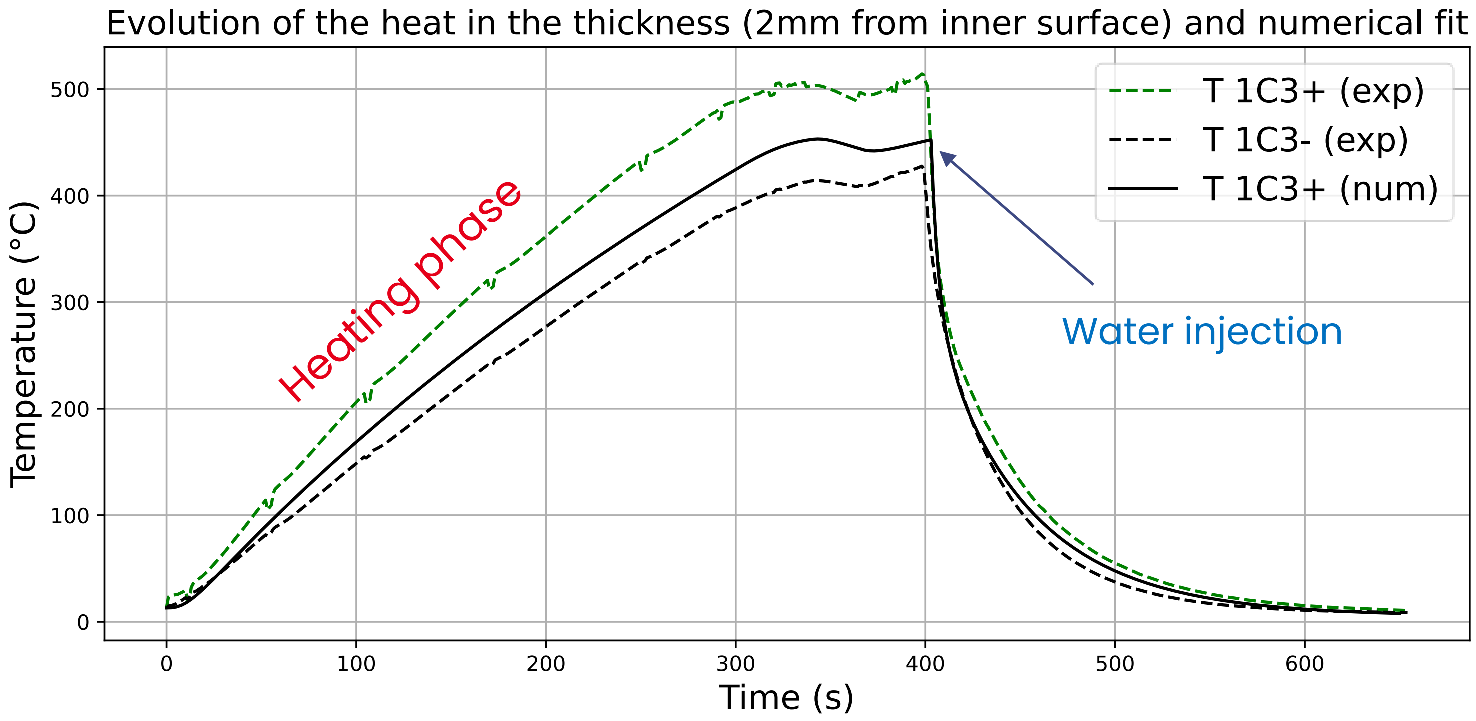
Third Step – rig development





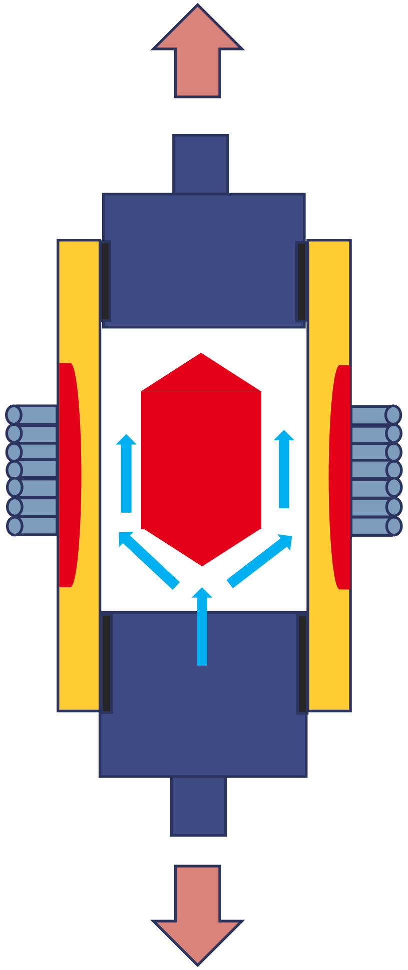


Fourth Step - Experiments and thermal FEM calibration



42 thermocouples data fitted numerically to reproduce the real thermal behavior of the pipe

Fifth Step – Final experiment and Numerical prediction



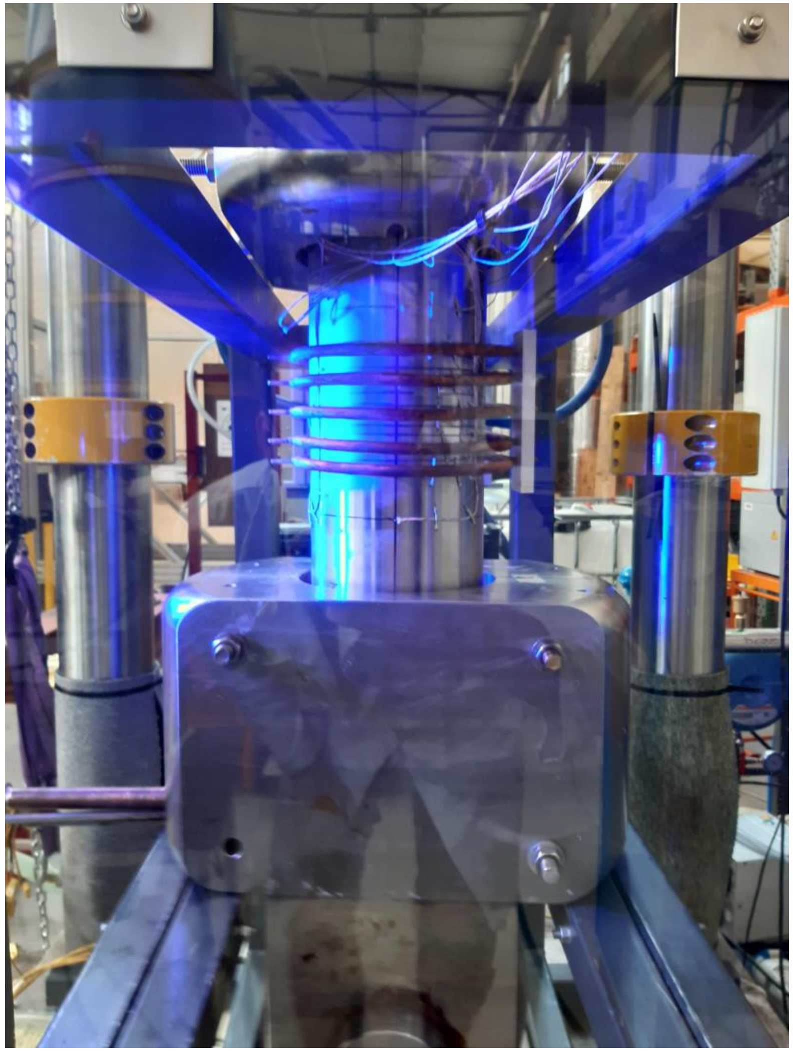
1) Installation of the pipe of the coil, and of lower clamping part

2) Installation upper clamping part and of tensile stress

3) Heating until max temperature then stabilisation

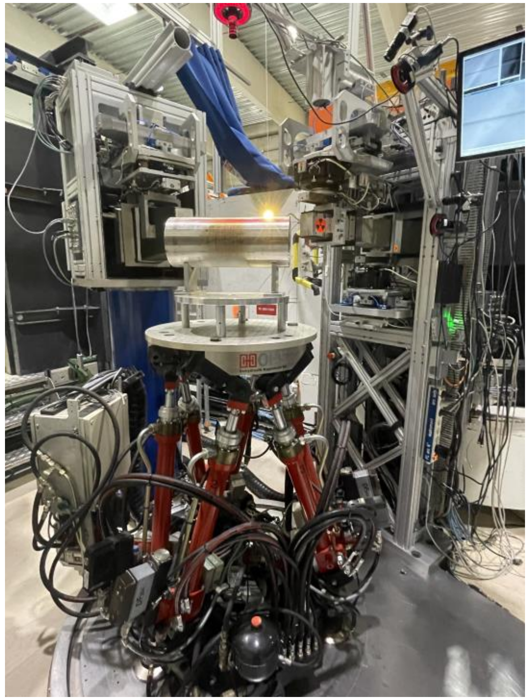
4) Water injection through lower clamping to produce thermal shock on inner surface

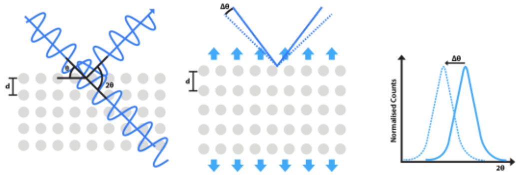
Fifth Step – Final experiment and Numerical prediction



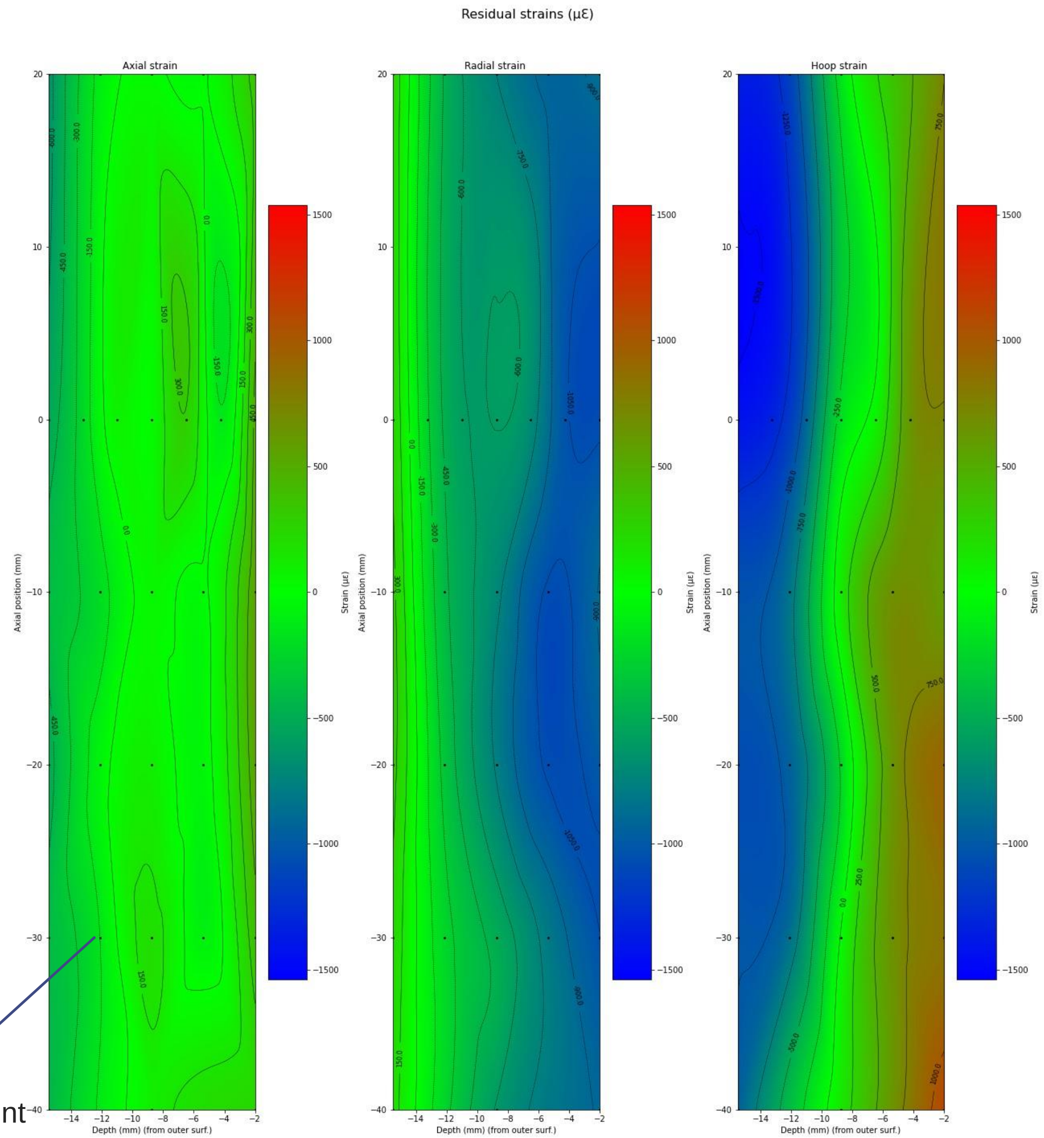
- Applied tensile force of 1250 kN in the direction of the pipe axis during the whole process
- Induction heating up to 550°C on the middle of the pipe
- Thermal shock produced by 5°C-water injection inside the pipe
- Use of Digital Image Correlation (DIC) to map the displacements and deformation on the outer surface

Sixth Step – ILL neutron diffraction measurements



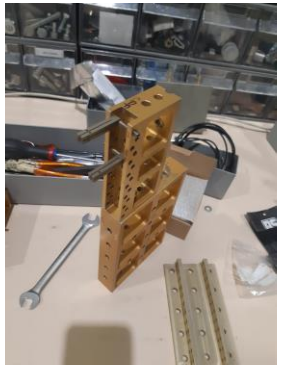


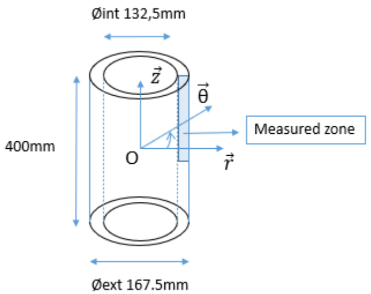
$$\varepsilon_{hkl} \equiv \frac{d_{hkl} - d_0}{d_0}$$



black dot : Measured point

d0 samples

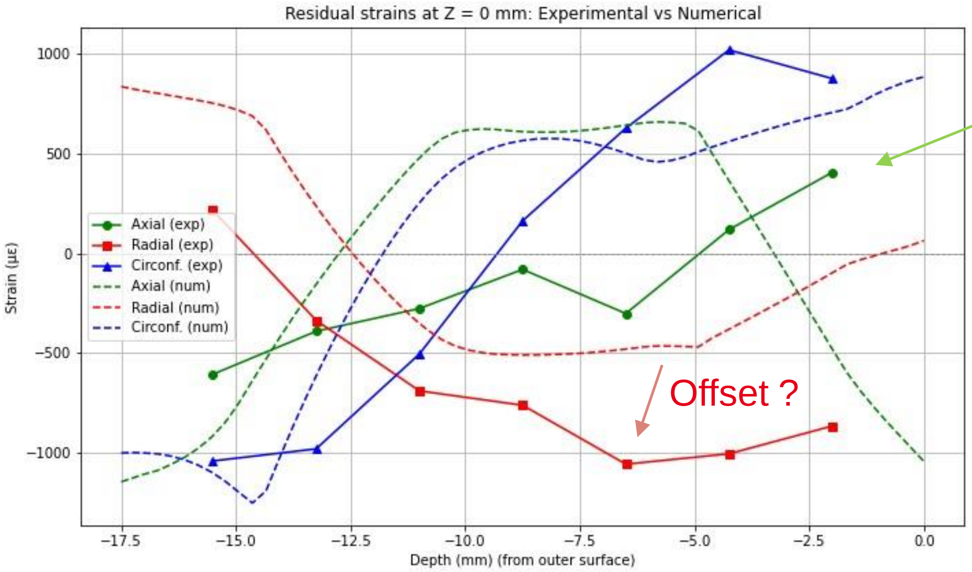




Presence of residual strains
Compressive hoop and axial strains at inner surface = typical of quench residual strains

Global strains are mainly compressive In the measured zone
Axial strains are way lower than the other components

Seventh Step – Experimental/numerical comparison part.1



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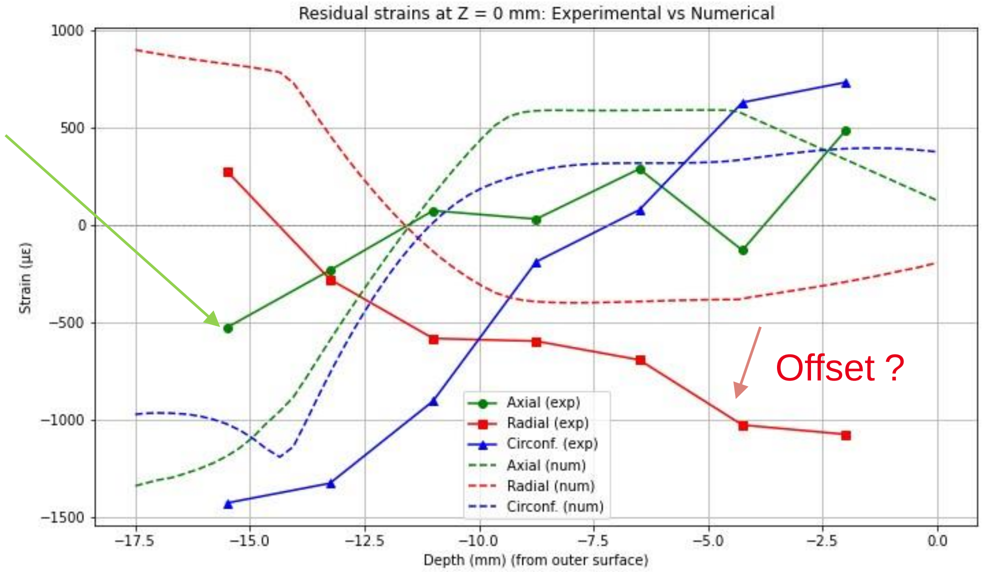


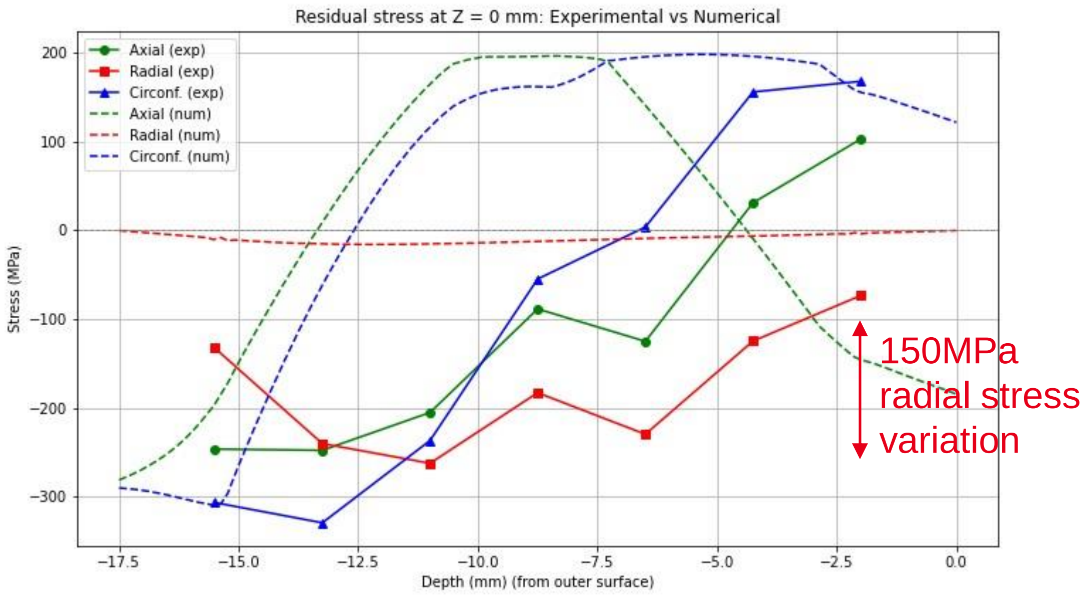
Small coil

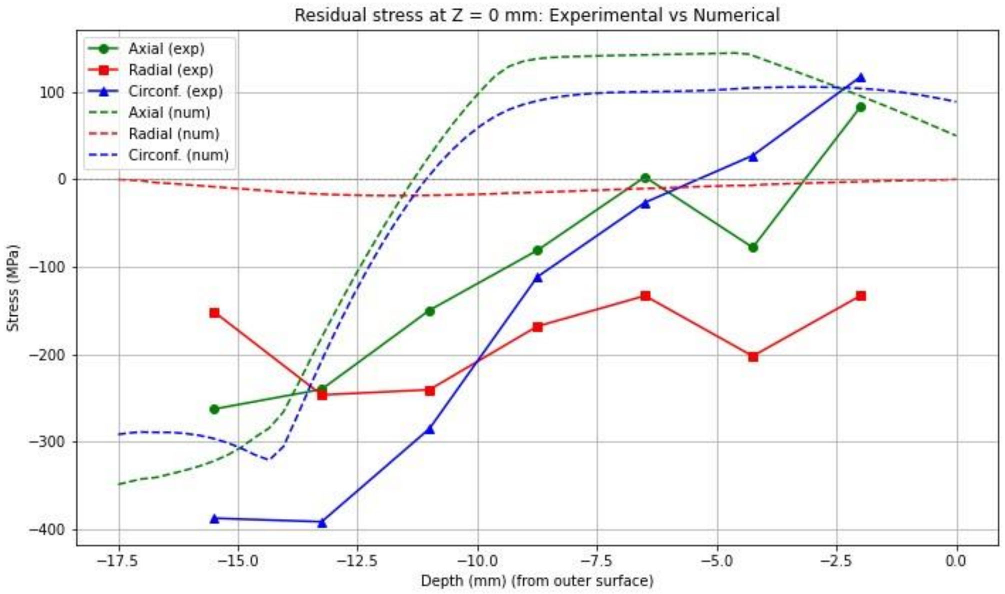
Large coil

For strains :

- Big offset on the radial strains
- Experimental axial strains are very different from numerical ones
- Both coil axial strains are similar

Seventh Step – Experimental/numerical comparison part.2





Small coil

Large coil

For stresses :

- Most curves are completely in disagreement
- Radial stress is way too high to by physical
- Both coil axial stresses are similar

Isotropic Hooke's law :

$$\sigma_{xx} = \frac{E_{hkl}}{(1+\nu_{hkl})(1-2\nu_{hkl})}[(1-\nu_{hkl})\varepsilon_{xx} + \nu_{hkl}(\varepsilon_{yy}+\varepsilon_{zz})]$$

$$\sigma_{yy} = \frac{E_{hkl}}{(1+\nu_{hkl})(1-2\nu_{hkl})}[(1-\nu_{hkl})\varepsilon_{yy} + \nu_{hkl}(\varepsilon_{xx}+\varepsilon_{zz})]$$

$$\sigma_{zz} = \frac{E_{hkl}}{(1+\nu_{hkl})(1-2\nu_{hkl})}[(1-\nu_{hkl})\varepsilon_{zz} + \nu_{hkl}(\varepsilon_{xx}+\varepsilon_{yy})]$$

Eighth Step - Panic

- Introduction of residual stress ? ☑
- Predictive ? ✖ Numerical model unable to reproduce the measured fields
- Multiple RSF possibilities ? ~ less than expected impact of the heating height from measurement data
- Interesting stress fields ? ~
- Similarities with Welding ones ? ~

What went wrong ? ➡ For now let’s focus on the numerical

Current work – Mystery solving

First test

Boundaries condition, elasto-plasticity material parameters, visco-plasticity , adding cooling from assembly mass, anisotropic elasticity, Kinematic hardening, using different software (Abaqus), decentered heating…

No effect

- The residual stress fields from the FEM are very stable in the experimental constraints
- None of the calculations are able to reproduce the offset of the radial strains/stress

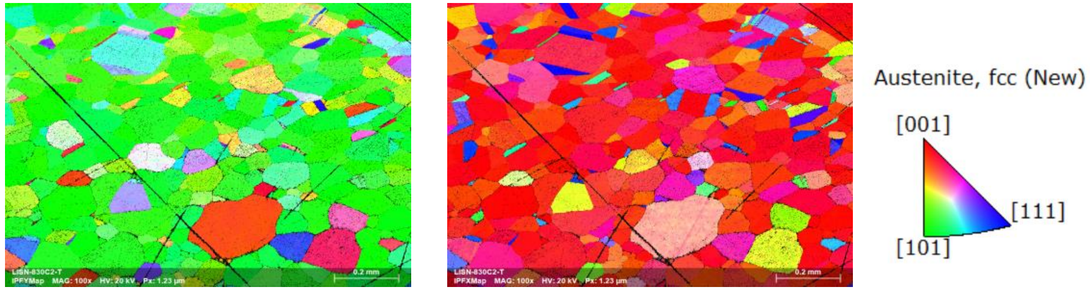
Other ideas

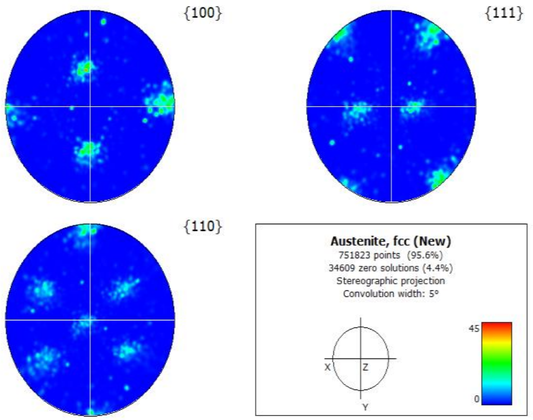
- Initial residual stress in the pipe (before experiment) ?
- Problem with experimental data ?

Texture causing anisotropic elasto-plasticity ?

Current work – Anisotropy study

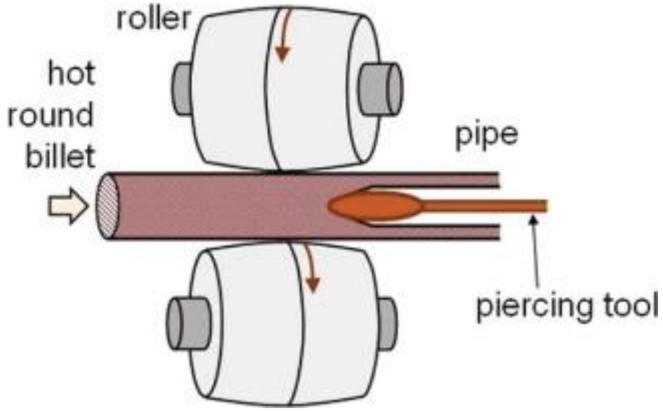
1) Do we have texture ?





2) Where does the material come from ?

Tubacex ASTM-ASME TP312 316-316L
Seamless tube forming



For austenite (FCC) :

We expect mechanical anisotropy to be less than 20% of yield limit variation

Current work – Anisotropy study

Hill orthotropic plasticity criteria via Mfront :

$$f(\boldsymbol{\sigma}) = \sqrt{\boldsymbol{\sigma}^{dev} : \boldsymbol{H} : \boldsymbol{\sigma}^{dev}}$$

$$\boldsymbol{H} = [F, G, H, L, M, N] = \begin{pmatrix} G+H & -H & -G & 0 & 0 & 0 \\ -H & F+H & -F & 0 & 0 & 0 \\ -G & -F & F+G & 0 & 0 & 0 \\ 0 & 0 & 0 & 2L & 0 & 0 \\ 0 & 0 & 0 & 0 & 2M & 0 \\ 0 & 0 & 0 & 0 & 0 & 2N \end{pmatrix}$$

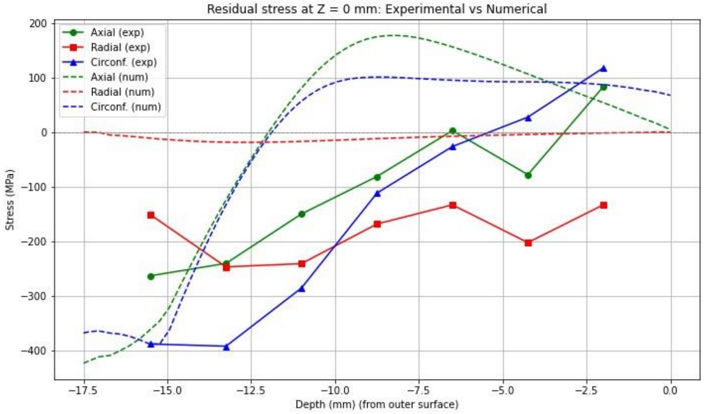
$$F = \frac{1}{2}\left[\frac{1}{(\sigma^y_{22})^2} + \frac{1}{(\sigma^y_{33})^2} - \frac{1}{(\sigma^y_{11})^2}\right]$$

$$G = \frac{1}{2}\left[\frac{1}{(\sigma^y_{11})^2} + \frac{1}{(\sigma^y_{33})^2} - \frac{1}{(\sigma^y_{22})^2}\right]$$

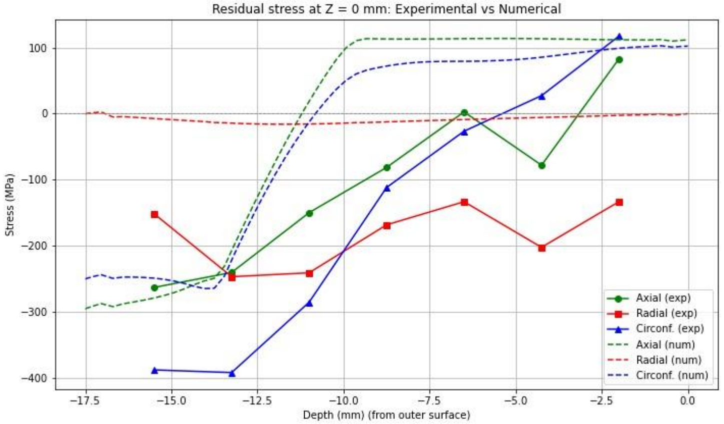
$$H = \frac{1}{2}\left[\frac{1}{(\sigma^y_{11})^2} + \frac{1}{(\sigma^y_{22})^2} - \frac{1}{(\sigma^y_{33})^2}\right]$$

Equivalent to modifying applied stress…
Doesn't explain our gap

Yield stress+20% on pipe axis



Yield limit-20% on pie axis



Current work – Problem with neutron diffraction behaviour in strongly textured samples

Literature :

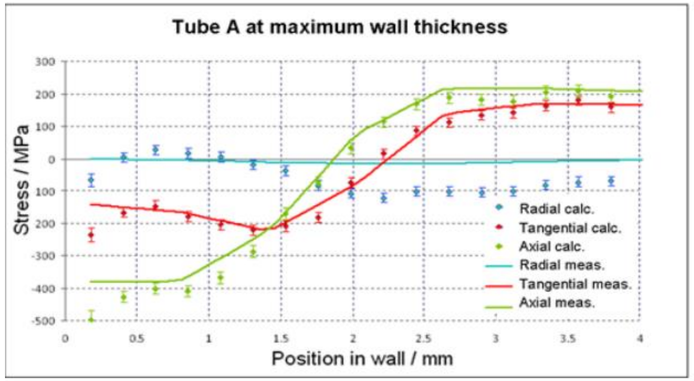
- X-Ray diffraction measurements : a lot of data => influence of texture + of triaxiality
- Neutron diffraction measurements : less data

⇒ some works on influence of texture + *garden engineering data corrections ?*

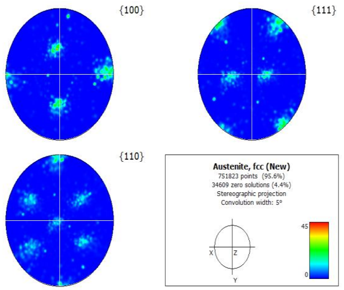
⇒ **usually at least 2 measurements methods are used**

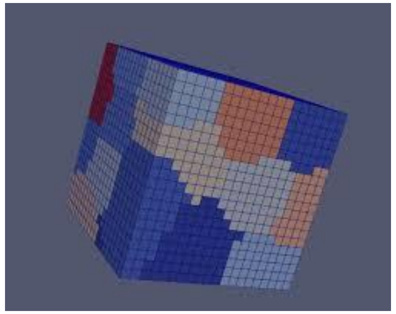
- Ongoing discussions with neutron diffraction experts/crystal plasticity

researchers modelling to correct residual stress measurement data

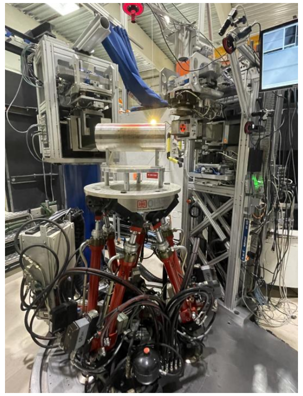


- MEB microstructure Study to develop CPFE model to correct residual stress





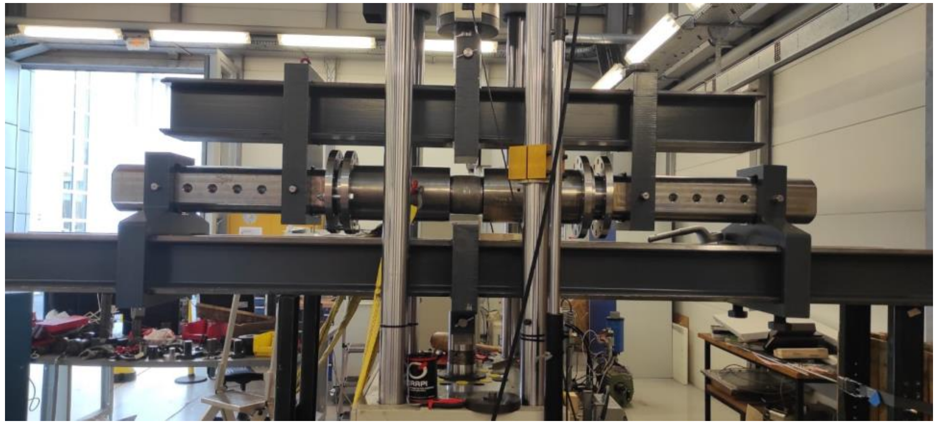
Reproduce measured strains and determine with inverse method the necessary stress to apply



Conclusion and future works

1 vs 0

- Cast3m numerical model is very consistent
- Validation of the numerical model with the DIC measurements
- Fatigue crack growth experiment on 8 point bending rig



Thank you

“I wouldn’t say it was a failure, I would say that it didn’t work”
E. Macron 10/14/2020

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Current work – Mystery solving – Influence of plastic anisotropy ?

“A lesson from this study is that to accurately predict residual stresses and strains, one must be wary of seemingly reasonable simplifying assumptions such as neglecting mild plastic anisotropy”

Michael B. Prime, Amplified effect of mild plastic anisotropy on residual stress and strain anisotropy, International Journal of Solids and Structures, Volumes 118–119, 2017, Pages 70-77, ISSN 0020-7683, https://doi.org/10.1016/j.ijsolstr.2017.04.022.

→ Microstructure observations are in progress to justify this lead

→ Numerical calculations with arbitrary orthotropic behavior arriving soon

→ DIC measurements from the experiments are being processed in hope to constrain the orthotropic behavior