LIÈGE université Sciences Appliquées

Materials and Solid Mechanics

Accurate very-high temperature creep-life prediction of Incoloy 800H addressing effects of creep mechanism transition and nitridation

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[5]: Fonds de la Recherche Scientifique –F.R.S. –F.N.R.S., Belgium

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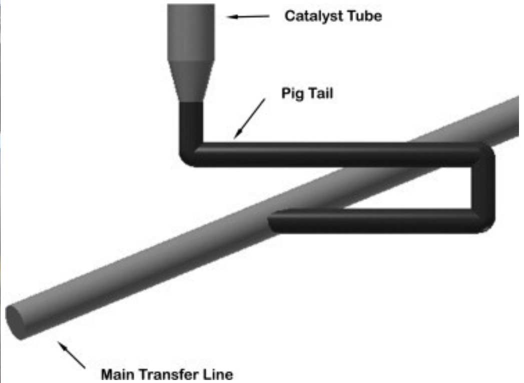
Incoloy 800H: a Fe-Ni-Cr austenitic alloy

- Solution annealing: 1150°C + WQ
- Microstructure:

- Austenitic (FCC)
- Grain twinning
- Intra- & intergranular precipitates
  - $M_{23}C_6$
  - M_6C
  - $Ti_x(C,N)$
- Average Grain Size $1 \leq \text{ASTM Gr.} \leq 5$

- Applications:
  - Petrochemical
  - Metallurgy
  - Heat exchangers
  - Power generation
  - ...

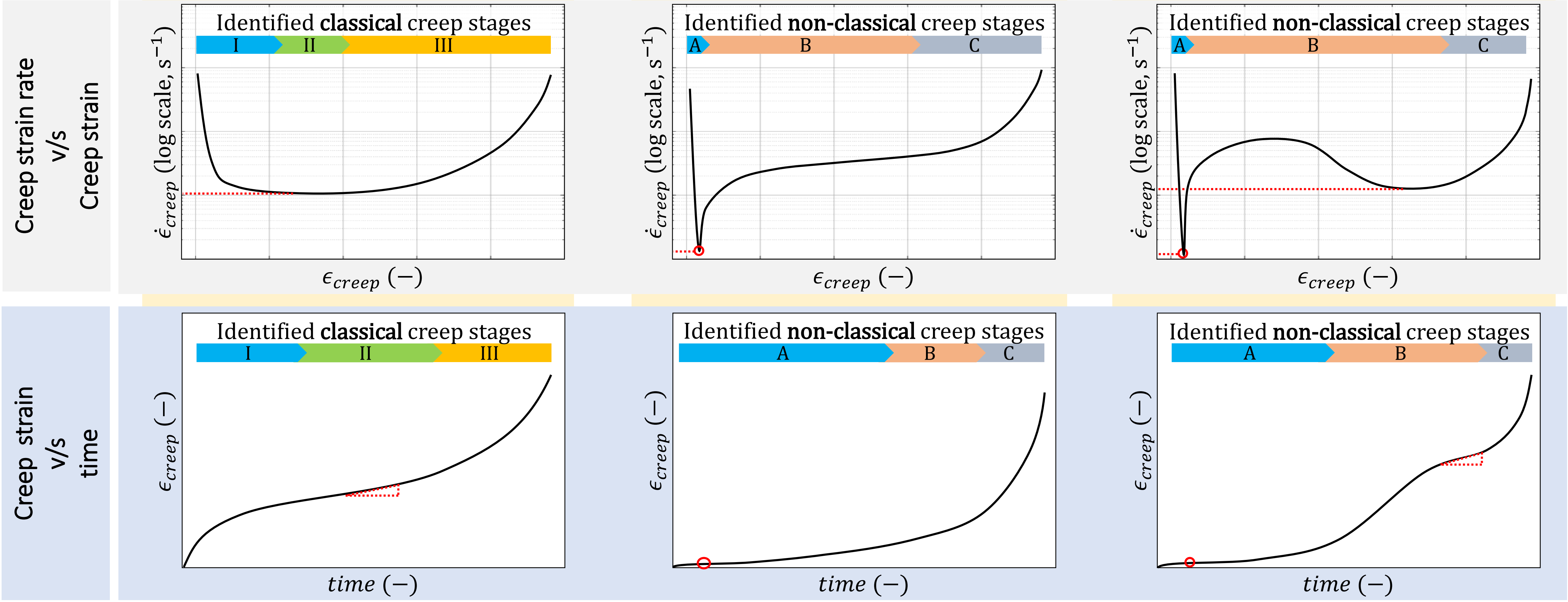


after *L.A. Spyrou et al., Eng. Fail. Anal., 2014*

Scientific context

Creep test

High-mid **stress** & Low-mid **T** $\sigma \gtrsim 40$ [MPa] | T° $\lesssim 760$°C	Low **stress** & high **T°** *Short creep test* | *inert gas test*	Low **stress** & high **T°** *Long creep test* | *non-inert gas test*

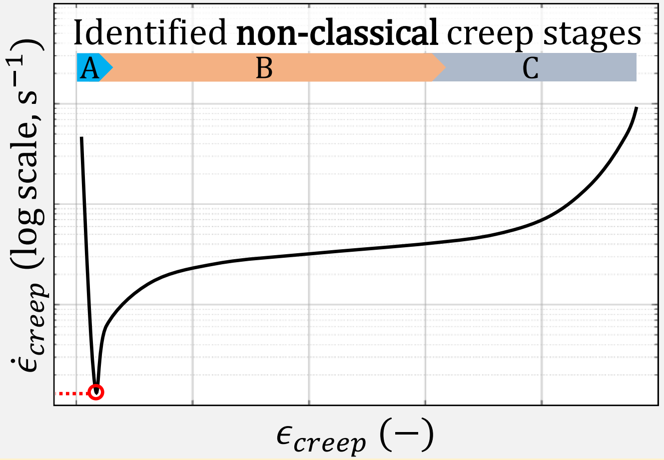


Creep test

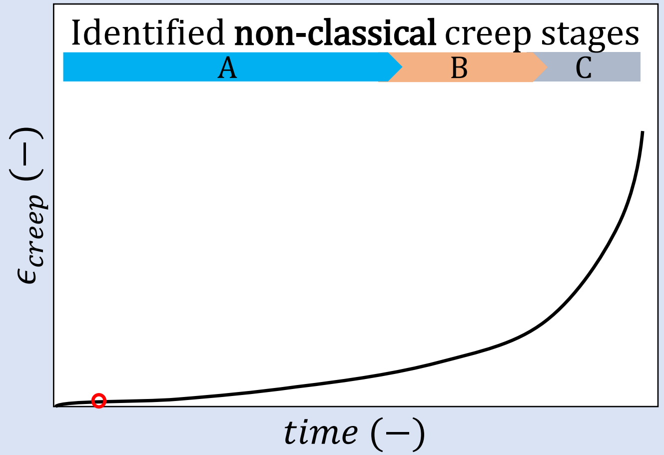
Low **stress** & high **T°**

Short creep test | inert gas test

Creep strain rate v/s Creep strain

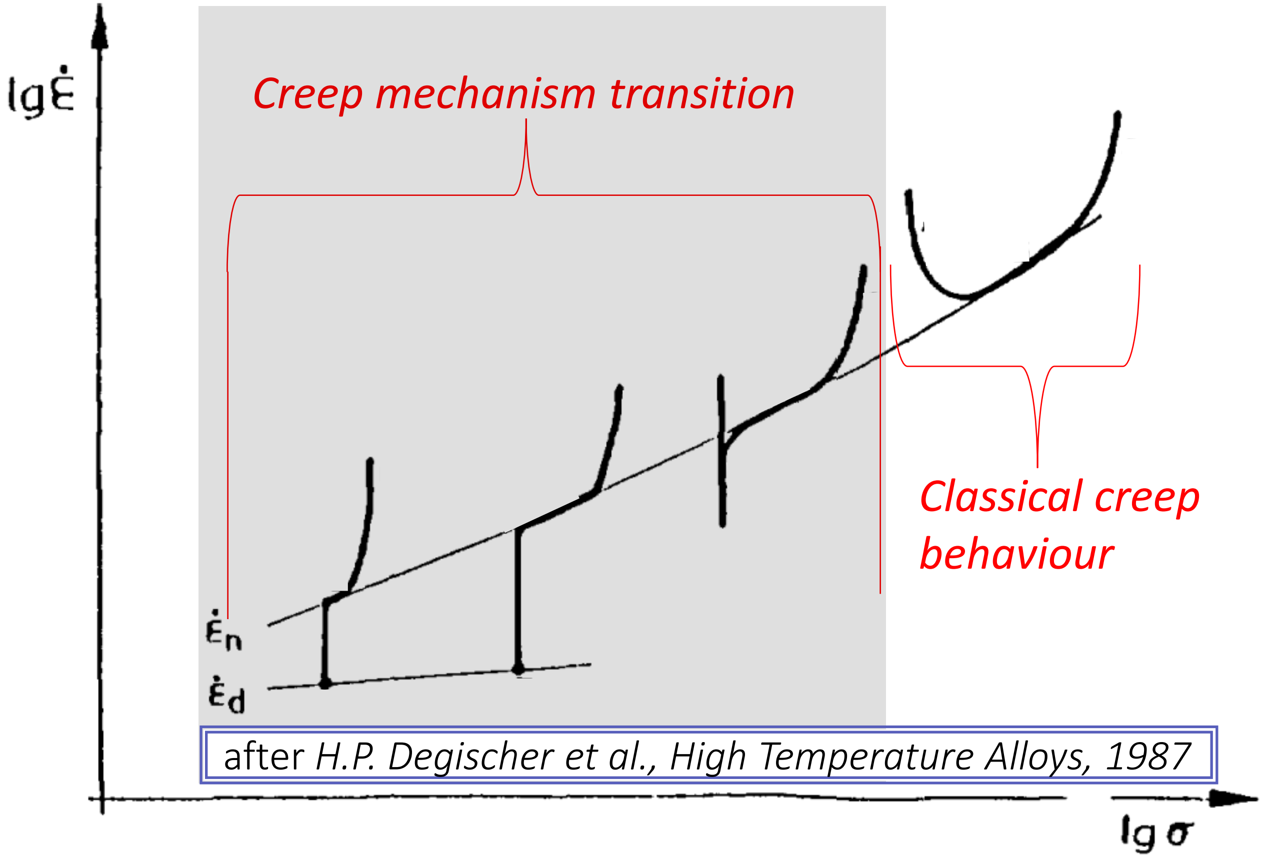


Creep strain v/s time



Explanation: creep mechanism transition

Qualitative creep rate – stress relation at 800°C



after *H.P. Degischer et al., High Temperature Alloys, 1987*

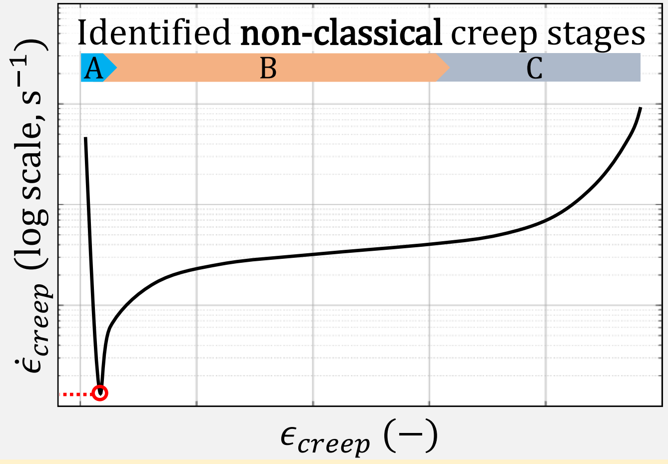
Scientific context

Creep test

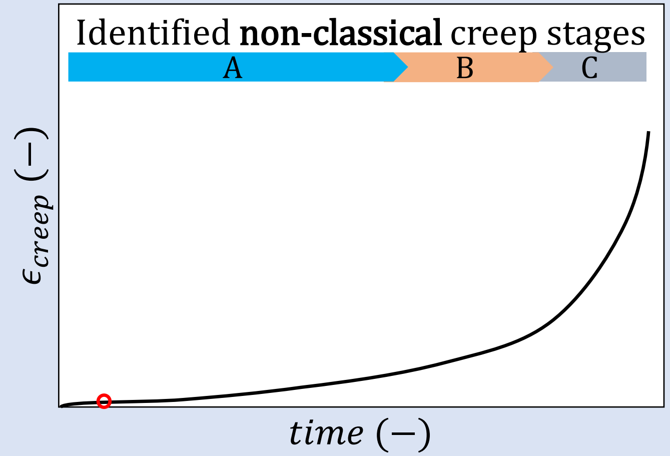
Low **stress** & high T°

Short creep test | inert gas test

Creep strain rate v/s Creep strain



Creep strain v/s time

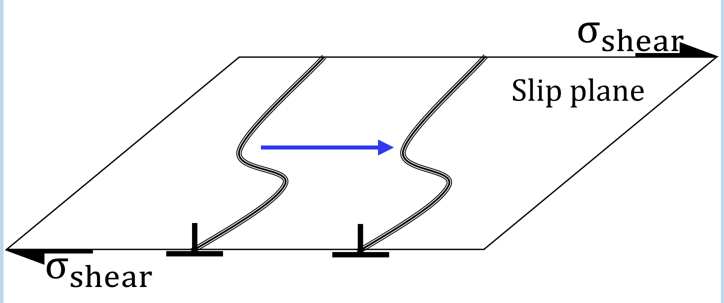


Explanation: creep mechanism transition

A — Dislocation-driven creep

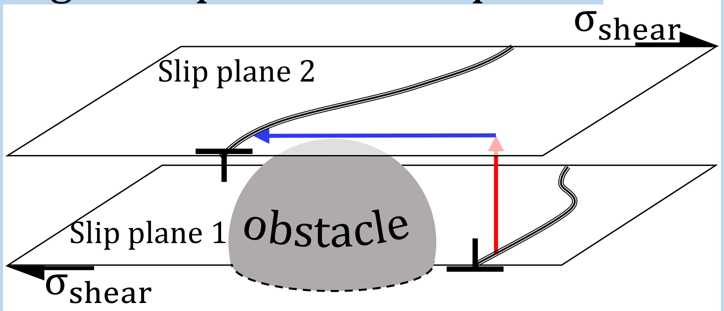
B — Diffusion-driven creep

Low-temperature creep



— Dislocation sliding

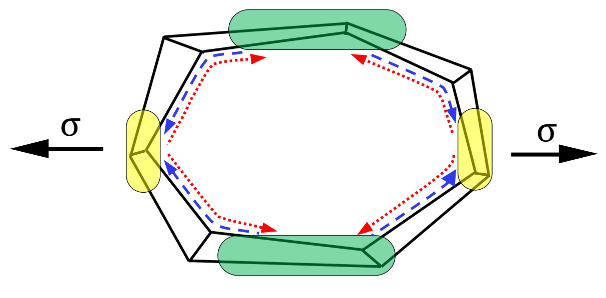
High-temperature creep



— Dislocation climbing

— Dislocation sliding

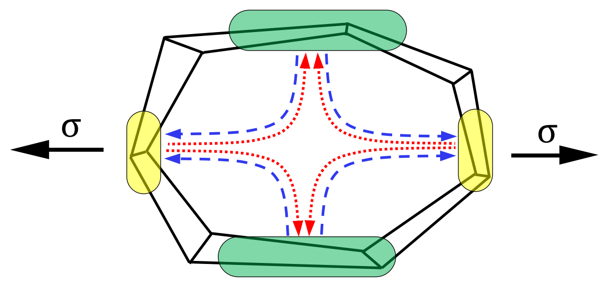
Coble creep



Vacancy current | Vacancy sink

Atom current | Atom sink

NHc: Nabarro-Herring creep



Vacancy current | Vacancy sink

Atom current | Atom sink

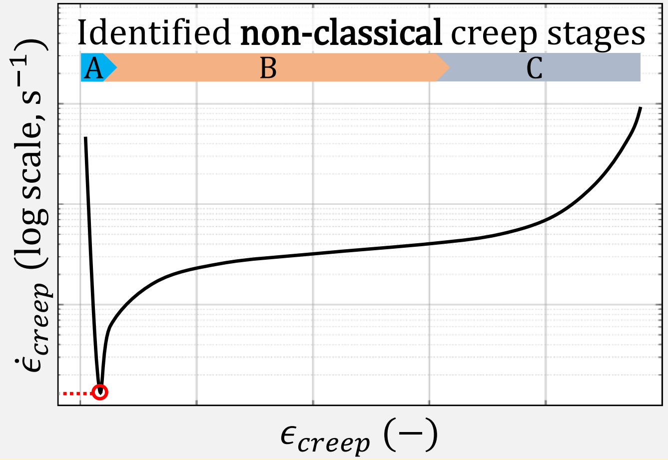
Scientific context

Creep test

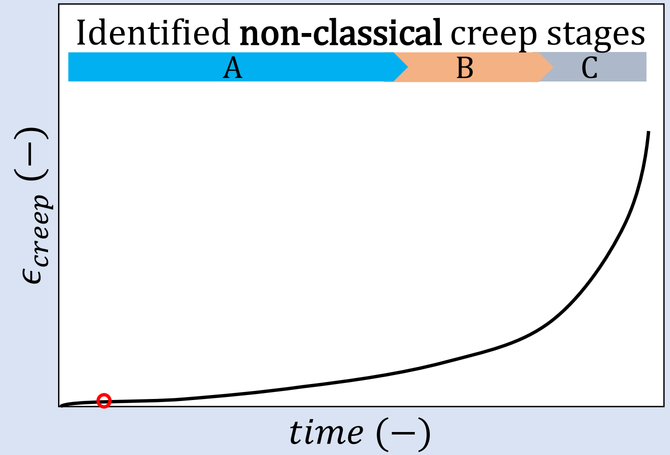
Low **stress** & high **T°**

Short creep test | inert gas test

Creep strain rate v/s Creep strain



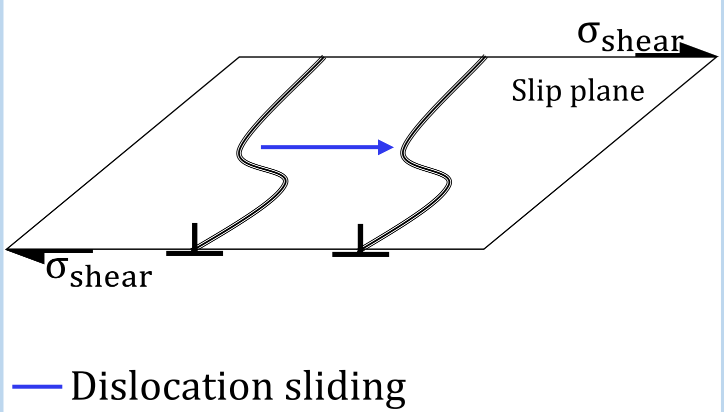
Creep strain v/s time



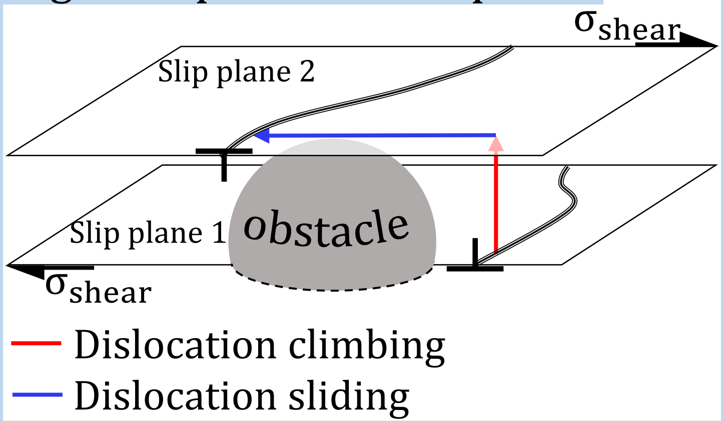
Explanation: creep mechanism transition

A Dislocation-driven creep

Low-temperature creep

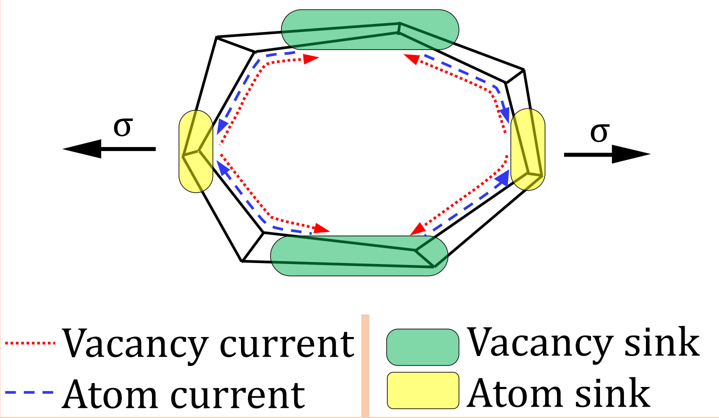


High-temperature creep



B Diffusion-driven creep

Coble creep



According to [*], intergranular diffusion (i.e., Coble creep) is the preferential diffusion-driven creep mechanism for 800H

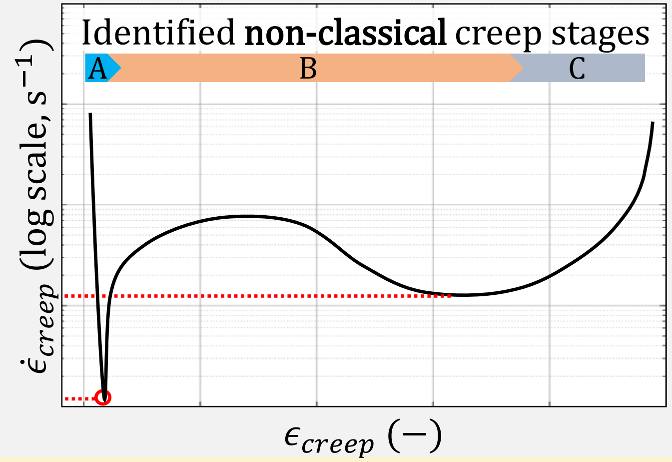
*: after *L.A. Beardsley et al., Metall. Mater. Trans. A, 2019*

Creep test

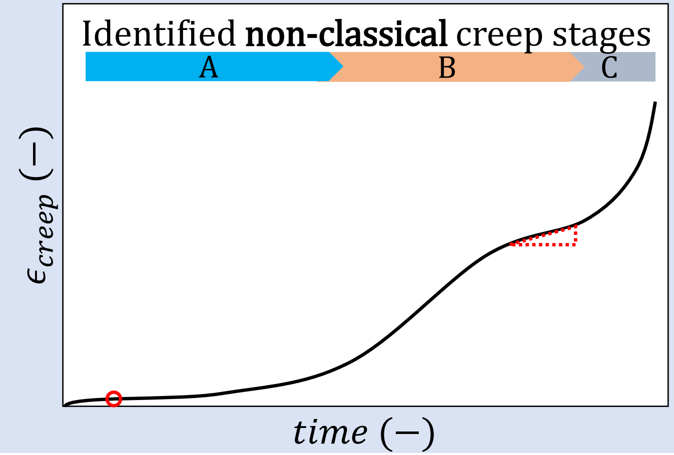
Low **stress** & high **T°**

Long creep test | non-inert gas test

Creep strain rate v/s Creep strain

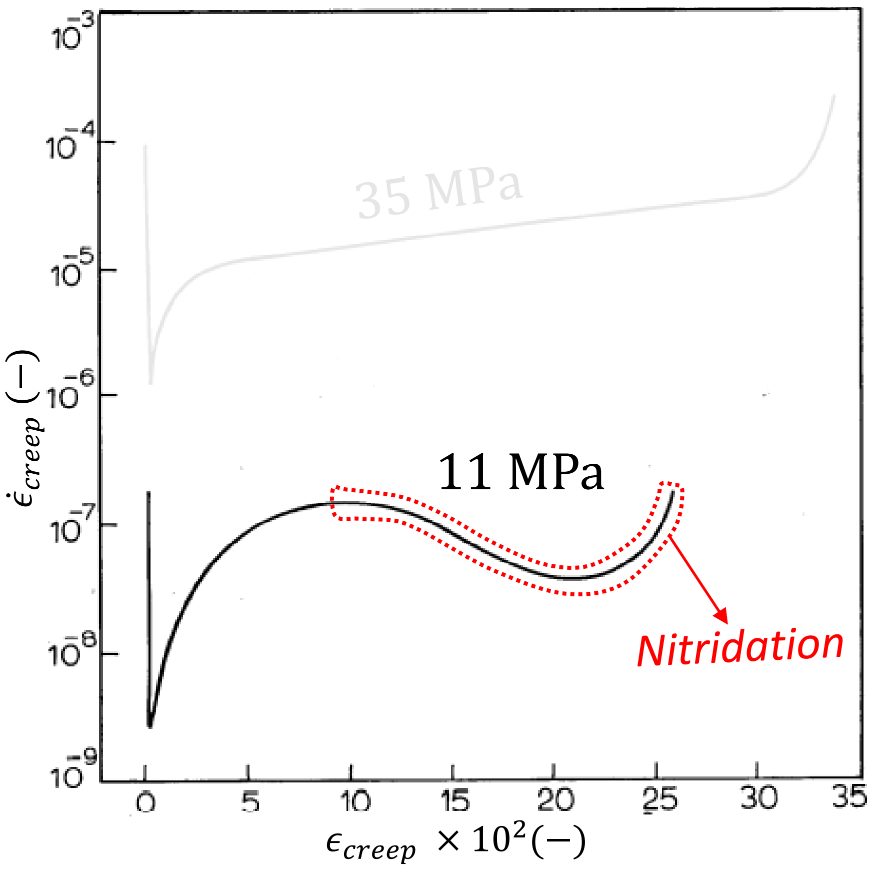


Creep strain v/s time



Explanation: Possible nitridation-induced creep hardening

1000°C creep-creep rate curves



Curves & micrograph after *V. Guttmann & R. Bürgel, Metal Science, 1983*

Finite Element numerical modelling of 800H alloy creep behaviour

Lagamine: Our finite element software

Developed since 1980s

- Large & small deformations
- Applied to many processes & many material behaviours
- Elasticity, Thermal, Viscosity,…

Step 1: Use available Chaboche-type constitutive model [*]

Yield function: von-Mises criterion

$$f_y = \Sigma_{VM}^{eq} - \sigma_y \leq 0$$

$$\underline{\tilde{\boldsymbol{\sigma}}} = (1-D)^{-1}\underline{\boldsymbol{\sigma}}$$ *Effective stress (effect of damage)*

$$\underline{\dot{\mathbf{X}}} = \sum_{i=1}^{n} \underline{\dot{\mathbf{X}}}_{\mathrm{AF},i} + \underline{\dot{\mathbf{X}}}_{\mathrm{SR},i}$$ *Hardening & Static Recovery*

$$\sigma_y = \sigma_0 + Q[1 - \exp(-b \cdot \bar{\epsilon}^p)]$$ *Voce isotropic hardening*

Viscoplastic function: Norton power law

$$\dot{\bar{\epsilon}}^p = \left\langle \frac{f_y}{K} \right\rangle^N \longleftrightarrow f_y = J_2(\underline{\tilde{\boldsymbol{\sigma}}} - \underline{\mathbf{X}}) - \sigma_y - K(\dot{\bar{\epsilon}}^p)^{1/N} \leq 0$$

Damage functions

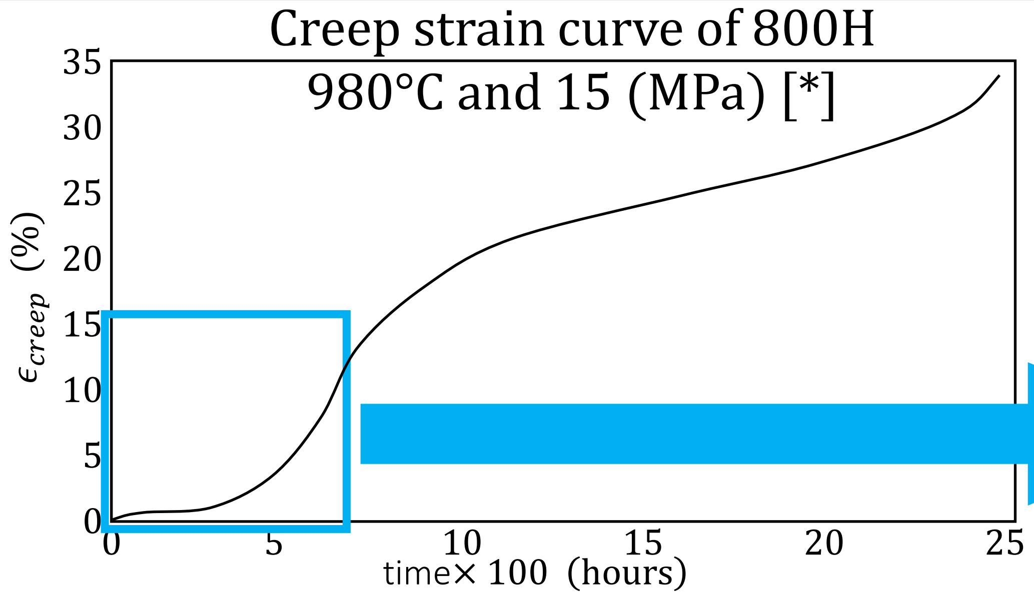
$$\dot{D} = \dot{D}_f + \dot{D}_c$$

$$\dot{D}_f = \left[\frac{Y(\sigma)}{S_{f1}}\right]^{S_{f2}} \dot{\bar{\epsilon}}^p$$

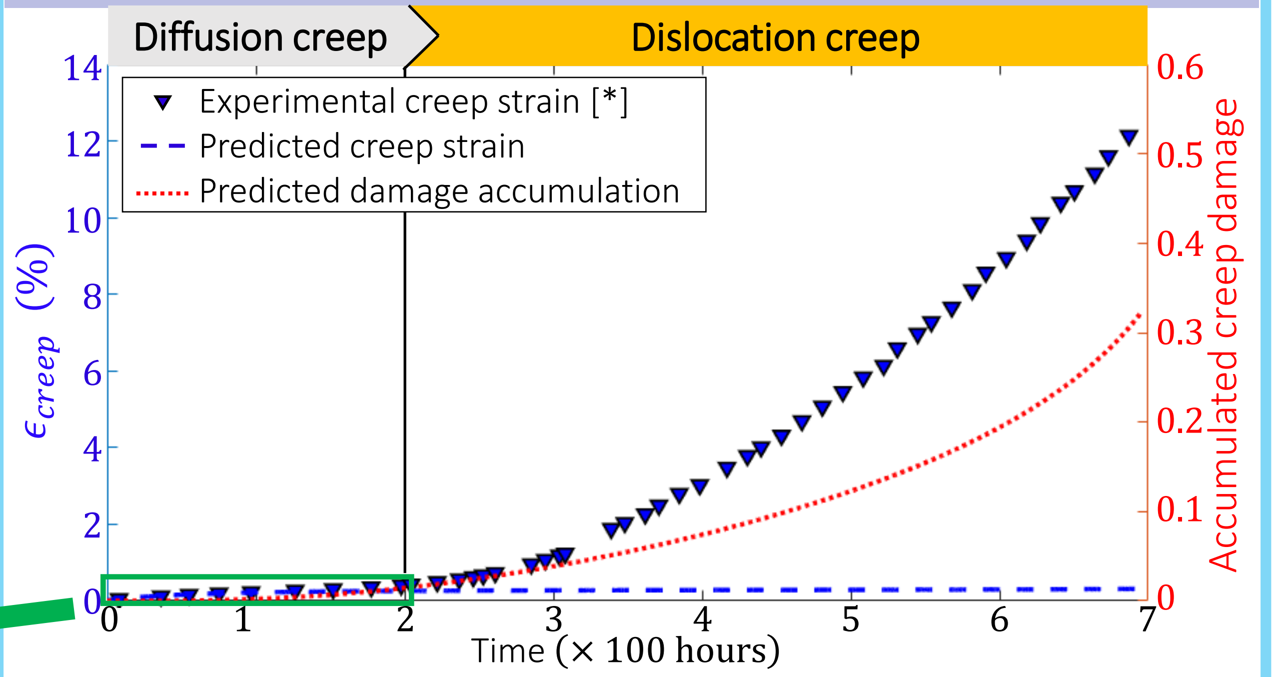
$$\dot{D}_c = \left[\frac{Y(\sigma^d)}{S_{c1}}\right]^{S_{c2}} \frac{1}{(1-D)^k}$$

*: Work after:
J.L. Chaboche, IJP, 2008; R. Ahmed et al., IJSS, 2016; R. Ahmed et al., IJSS, 2017;
H. Morch et al., COMPLAS, 2017; H. Morch et al., EJM: A/Solids, 2021; H. Morch et al., FE in A&D, 2022)

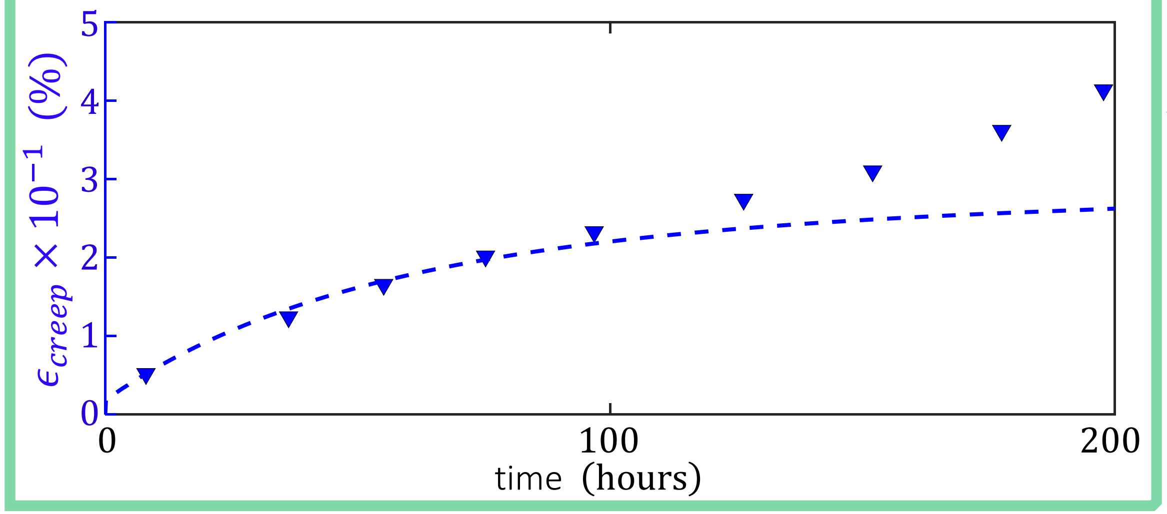
Scientific challenge



First modelling attempt, Chaboche-type law



*: experimental curve after *B. Gardiner, PhD. thesis, U. Canterbury, 2014*



- We must implement a macromechanical model capable of predicting non-classical creep behaviour observed in 800H alloy

Microstructure tests

Sample preparation

Smooth bar 800H samples

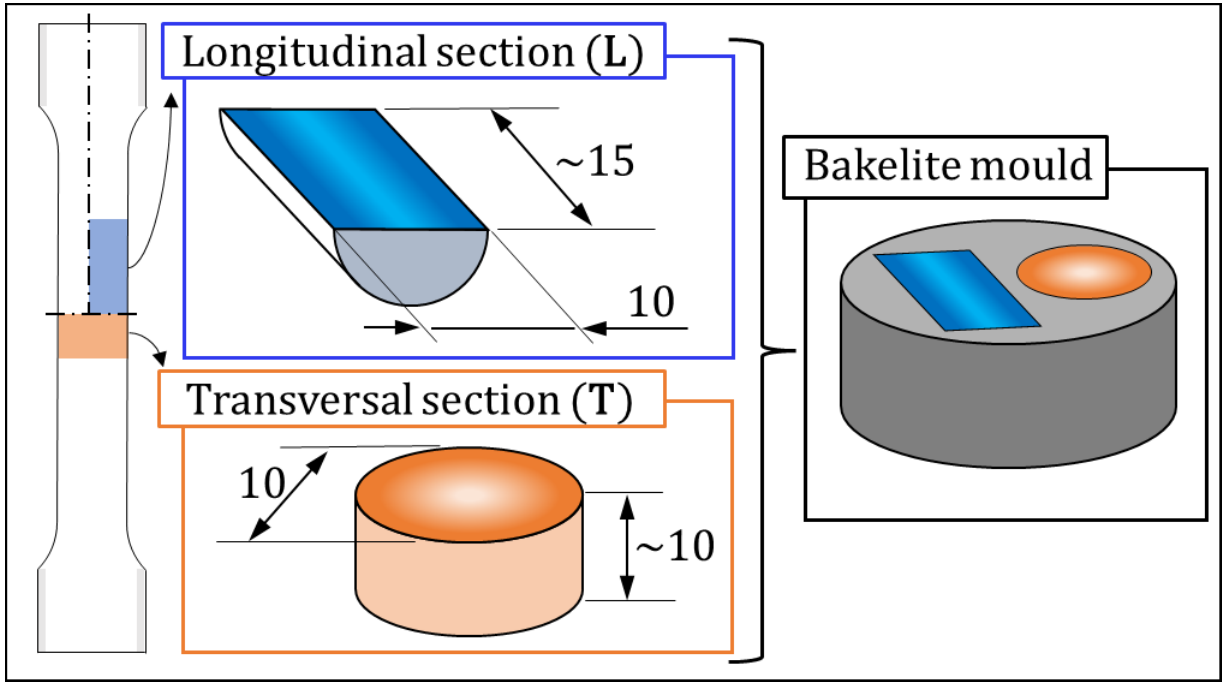
Geometries
- D05 5 [mm] diameter
- D10 10 [mm] diameter

Industrial furnace

Exposed to realistic environmental and thermal loadings

Tag	Description
N0	Sound material
N1	1 year in furnace
N2	2 years in furnace
N3	3 years in furnace
N4	4 years in furnace

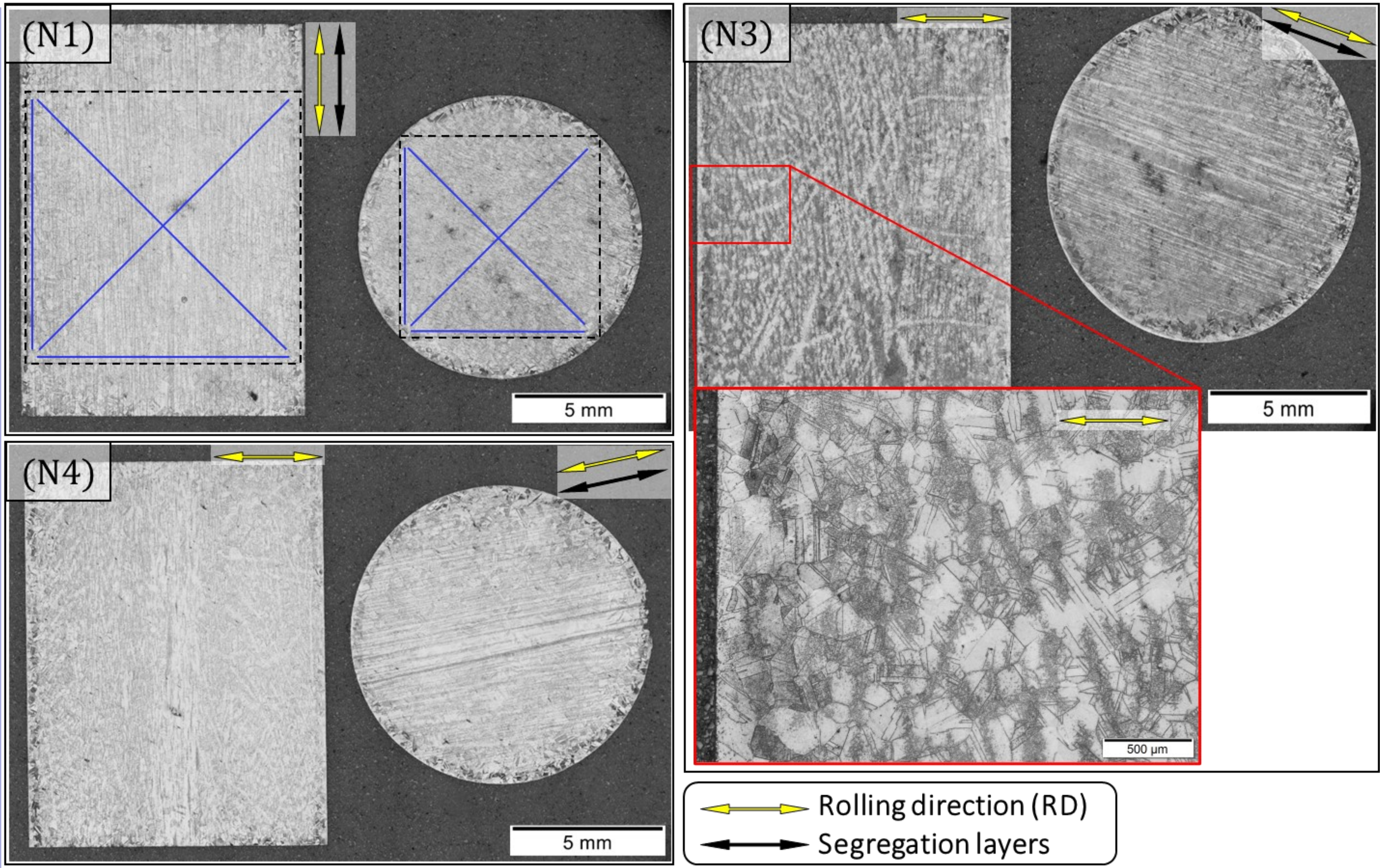
1 D10 sample from each N-batch was selected to undergo microstructural characterization



Microstructure tests

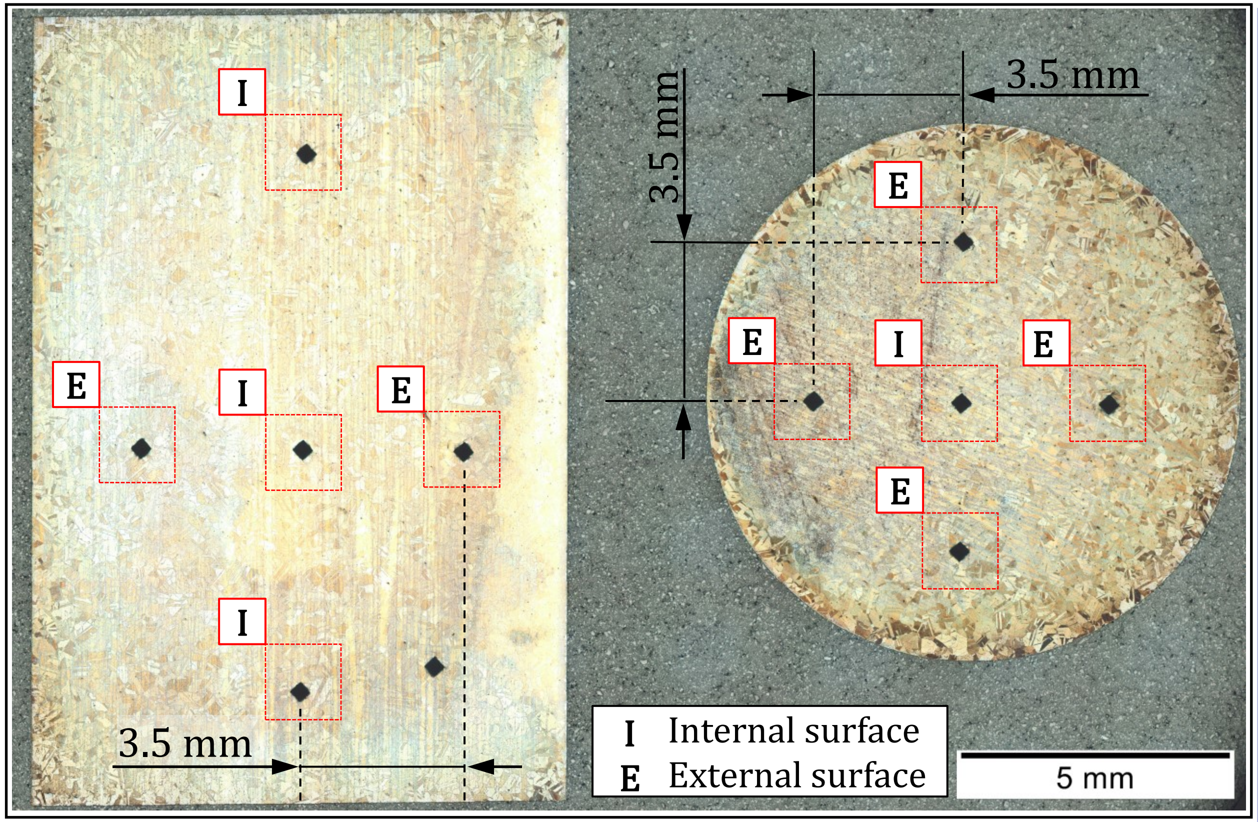
Optical microscopy* observations:

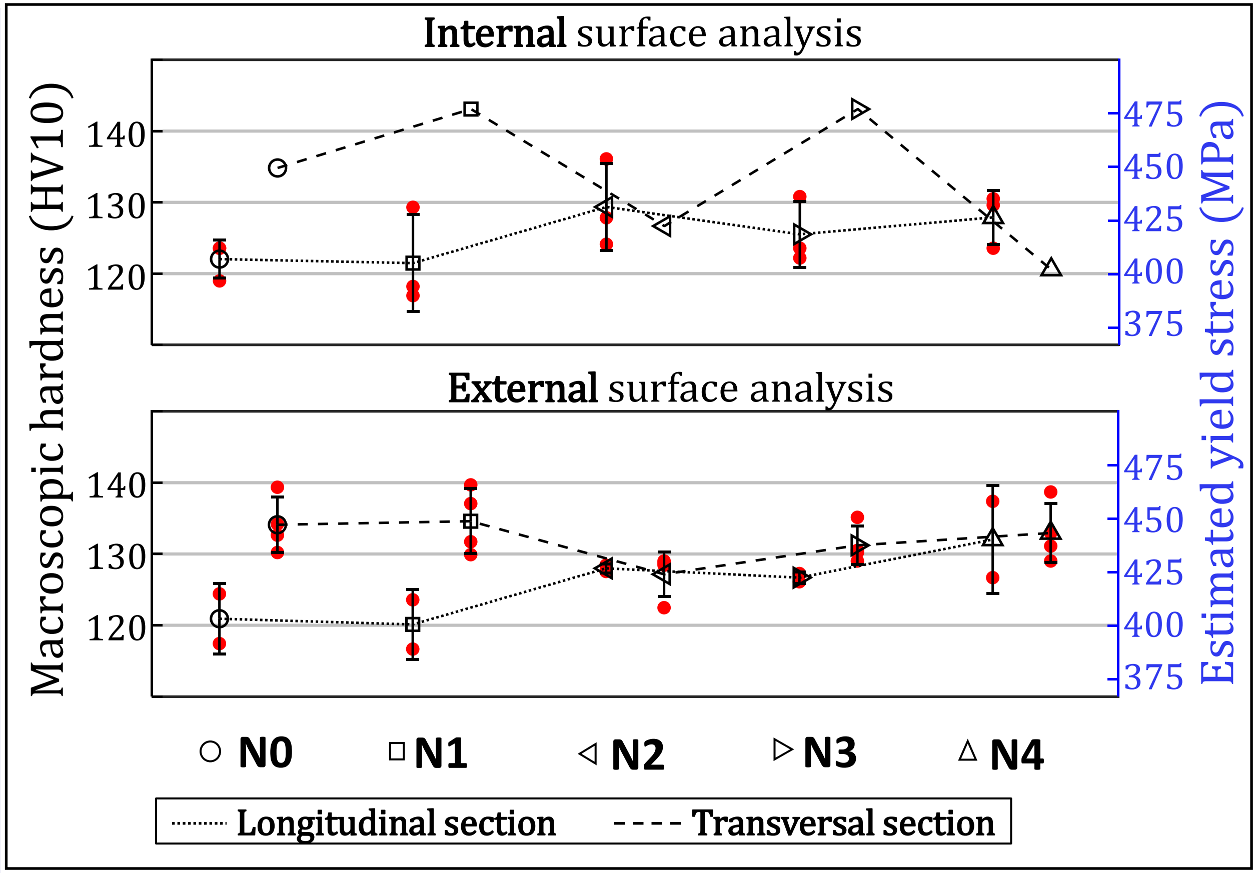
- AGS Gr.2 = 150 (µm)
- No visible external layer
- High precipitate segregation
  - Layers aligned to the RD
  - Dendritic-like segregation in N3



*:Etching compound: Glyceregia

Macro-indentation Vickers (HV10) observations:

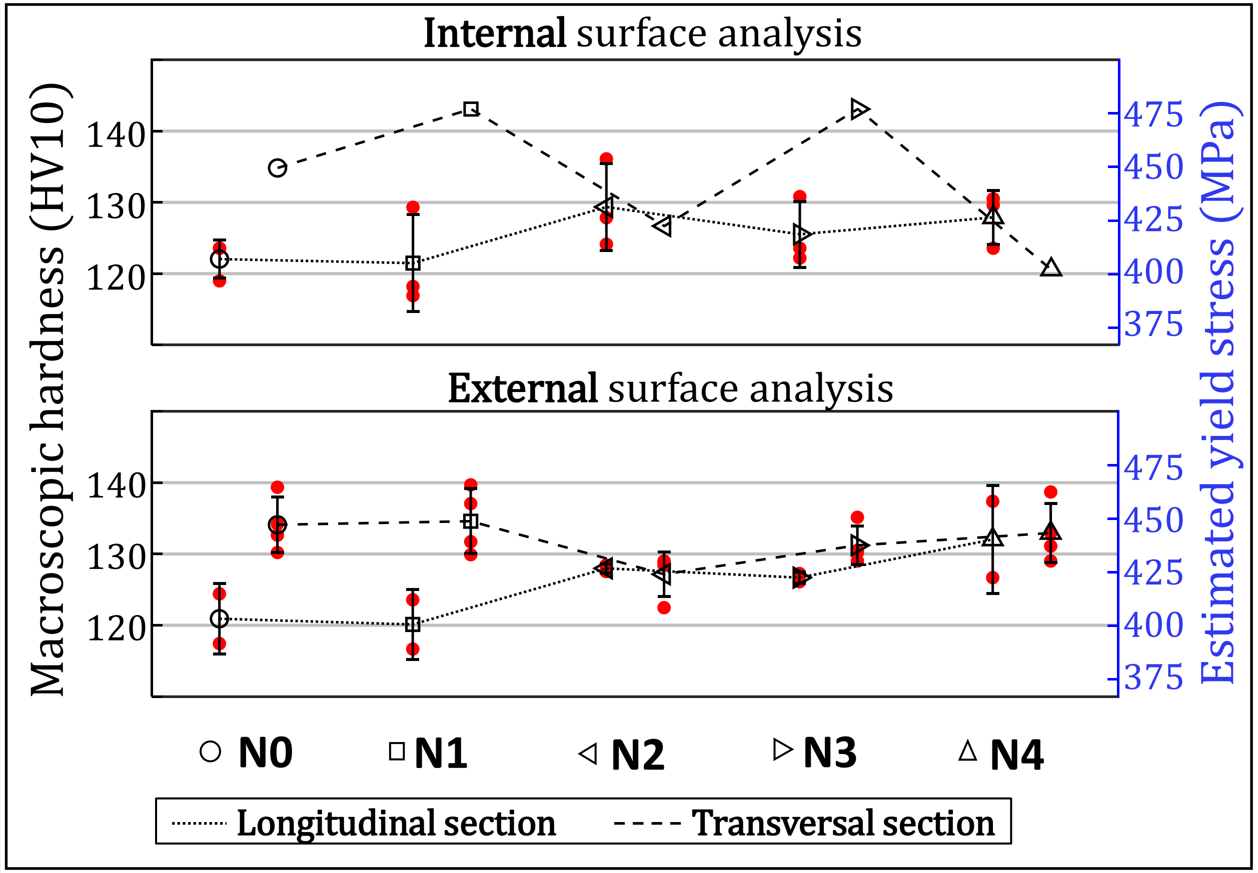




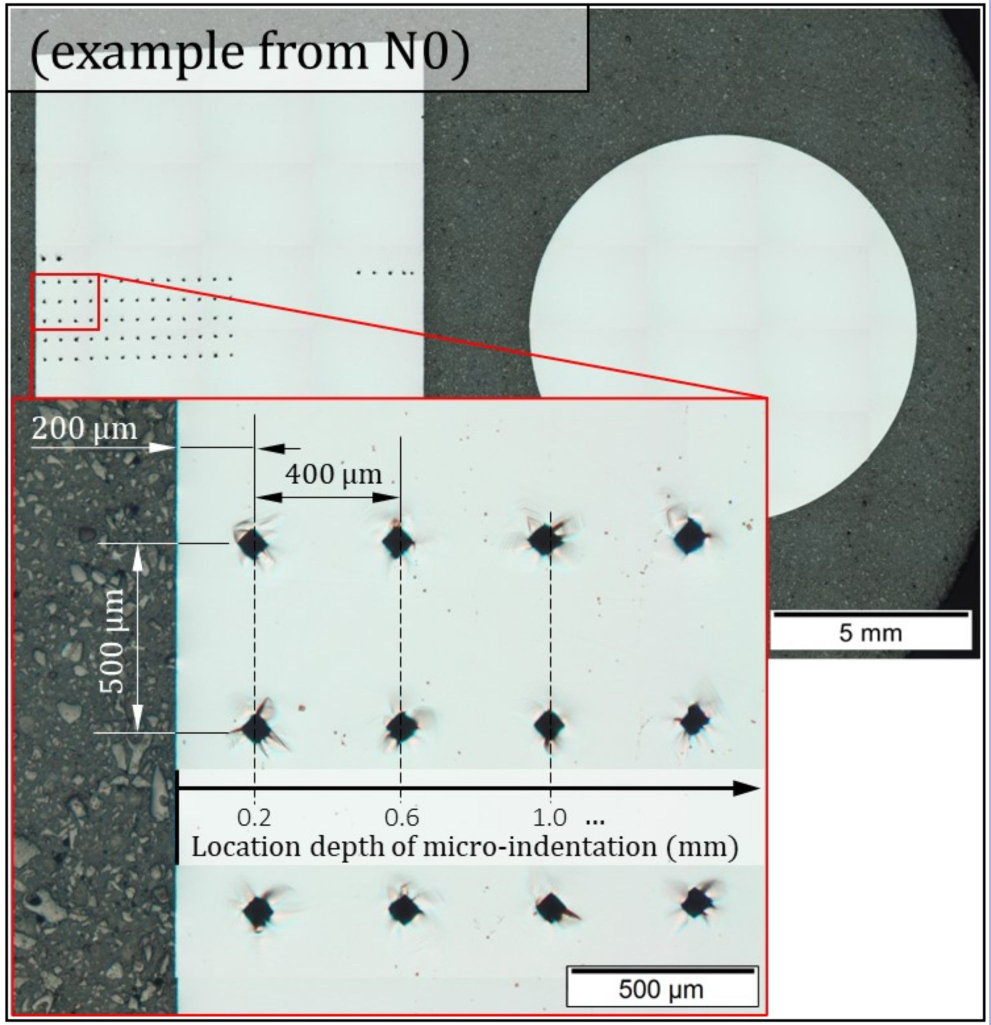
Macro-indentation Vickers (HV10) observations:

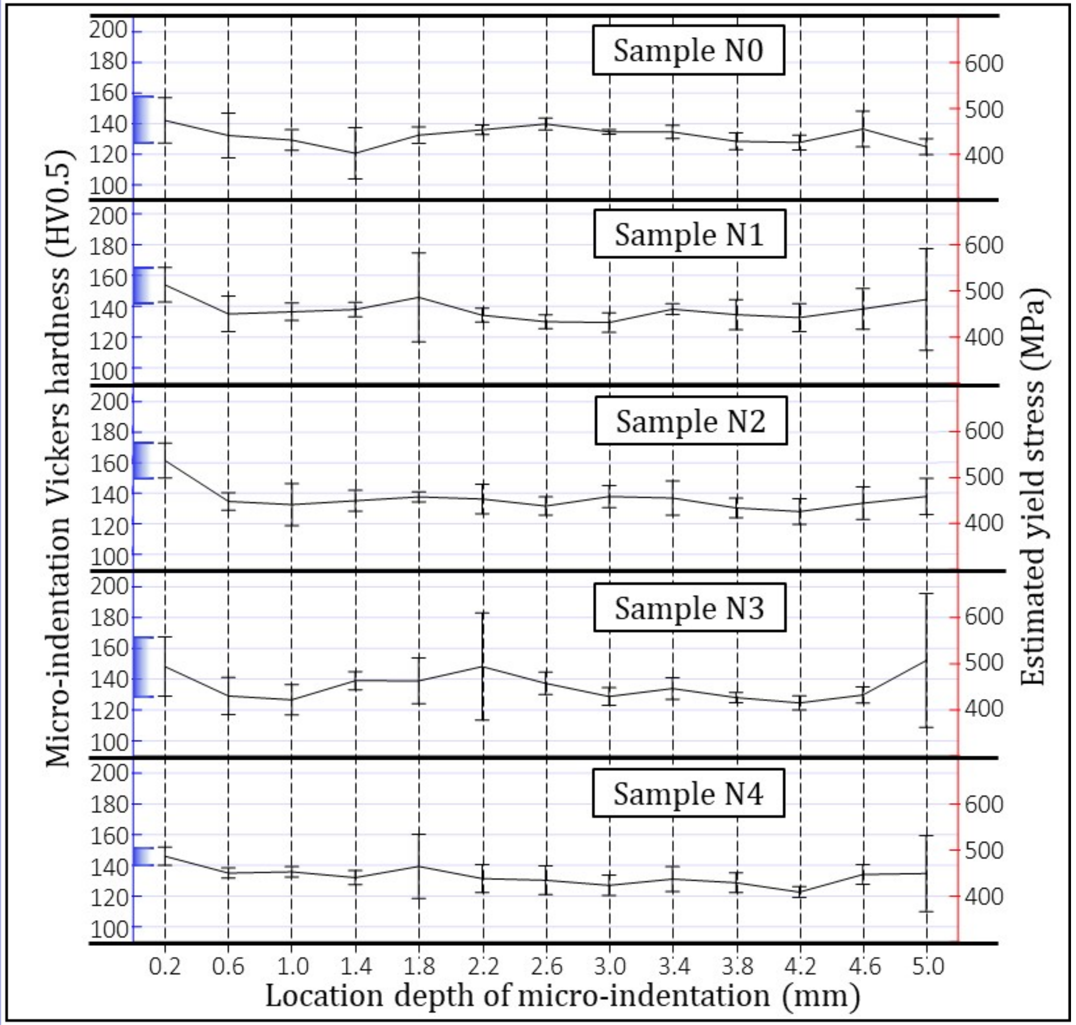
Important observations:

- High material inhomogeneity
- No clear hardening/softening trend in relation to years-in-furnace



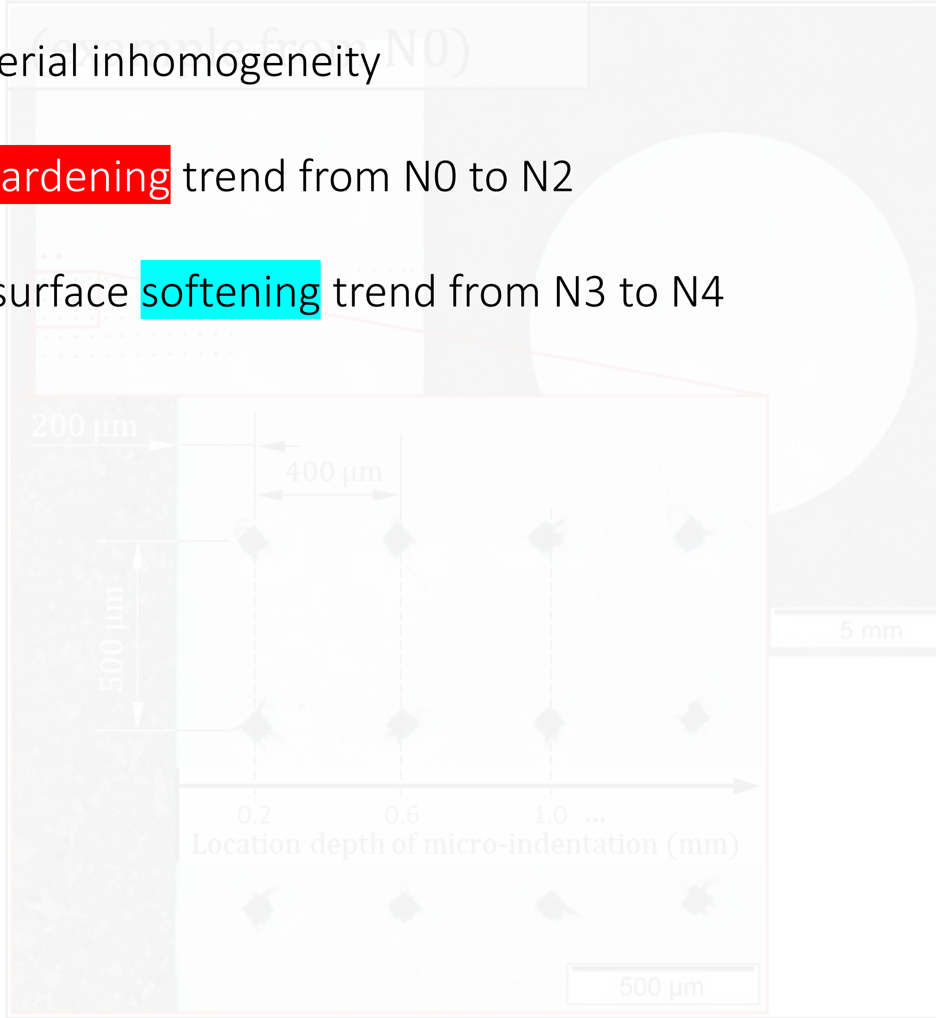
micro-indentation Vickers (HV0.5) observations:

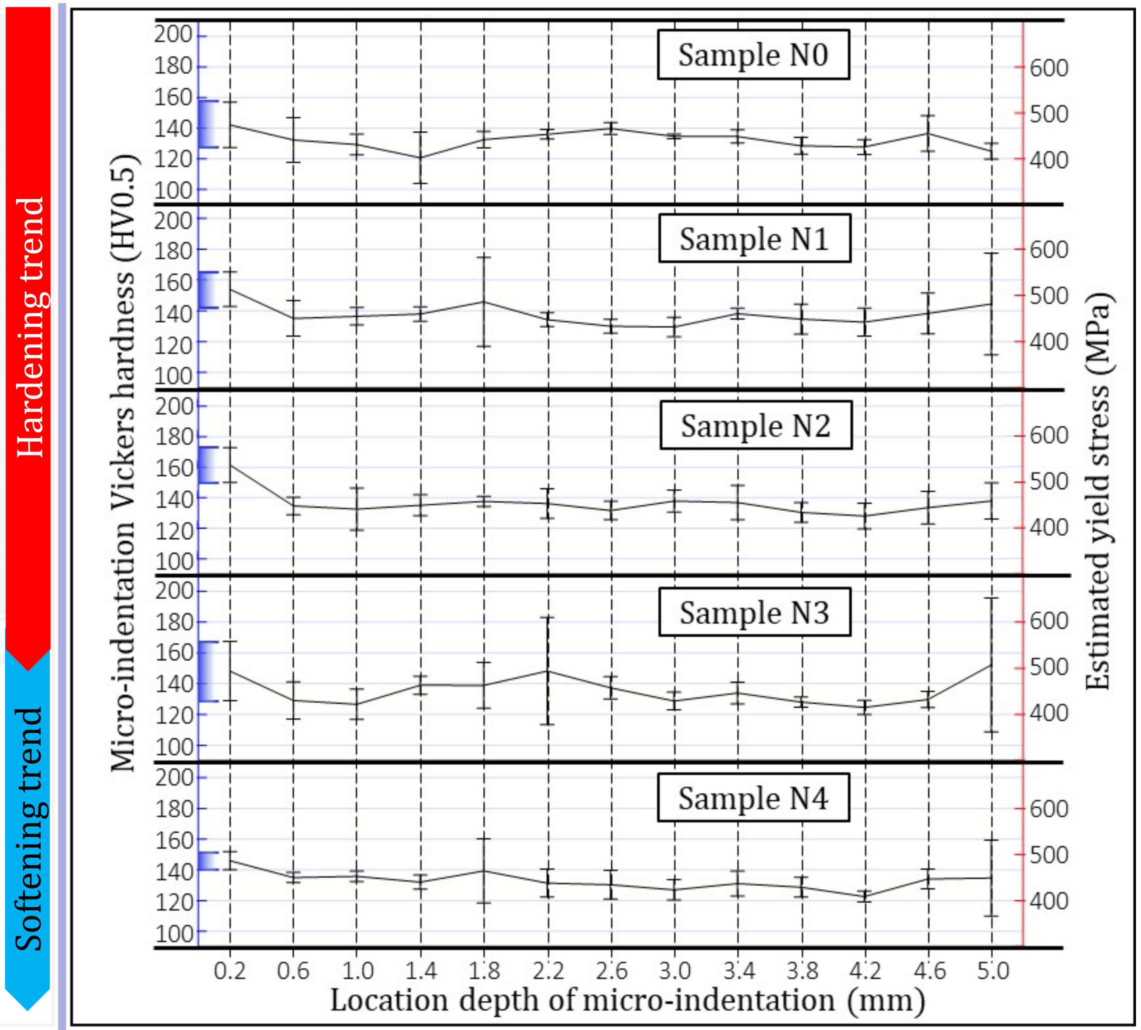




micro-indentation Vickers (HV0.5) observations:

- High material inhomogeneity
- Surface hardening trend from N0 to N2
- External surface softening trend from N3 to N4

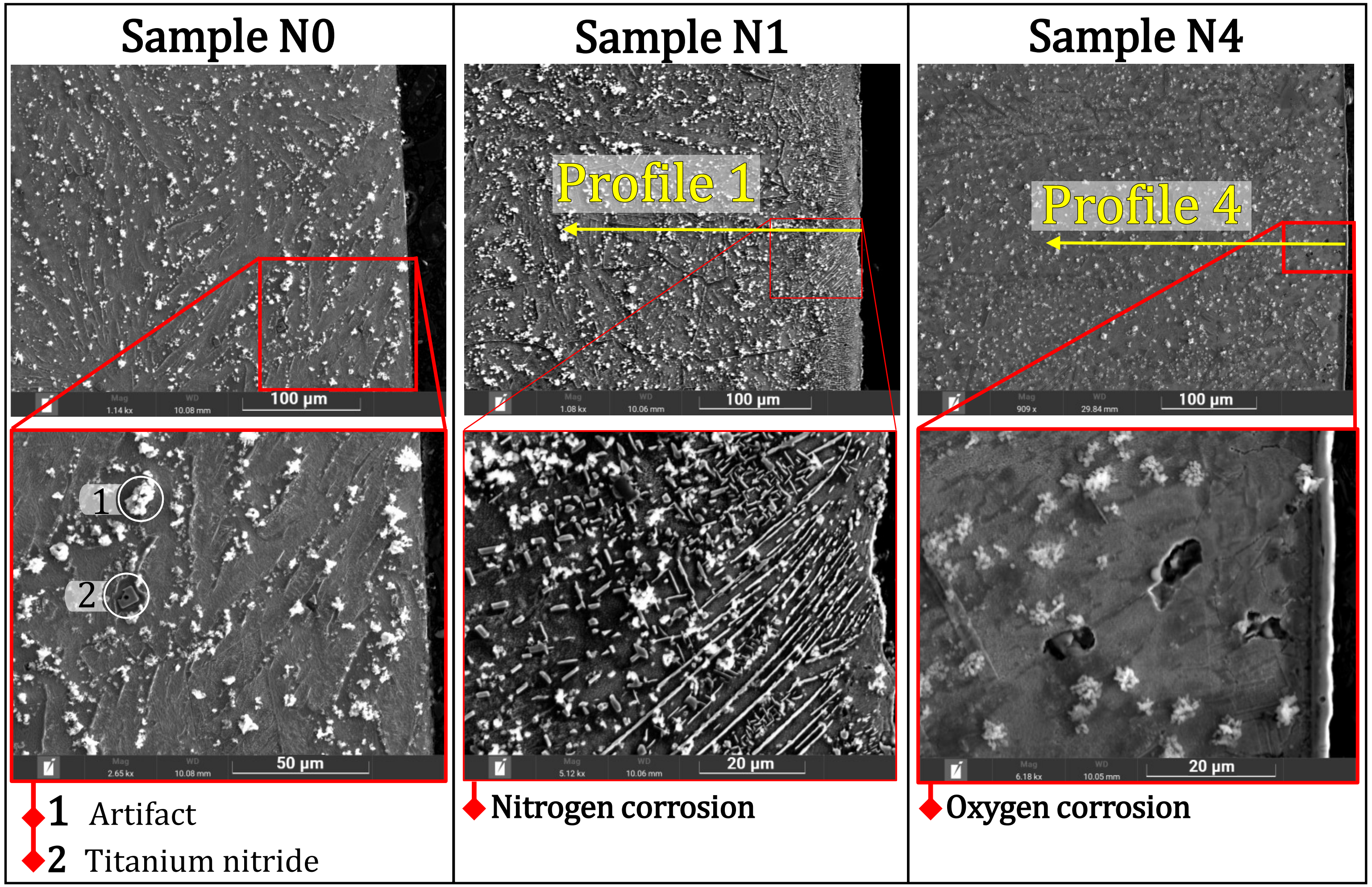




Microstructure tests

SEM/EDX observations:

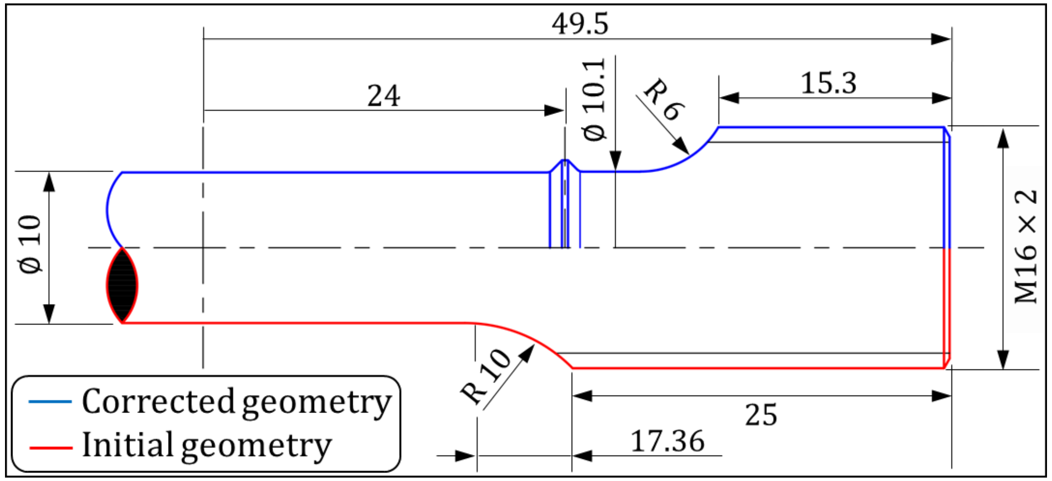
- Presence of artifacts
- Intergranular carbide precipitation
- **Nitridation** is dominant in sample **N1**
- **Oxidation** in dominant in sample **N4**

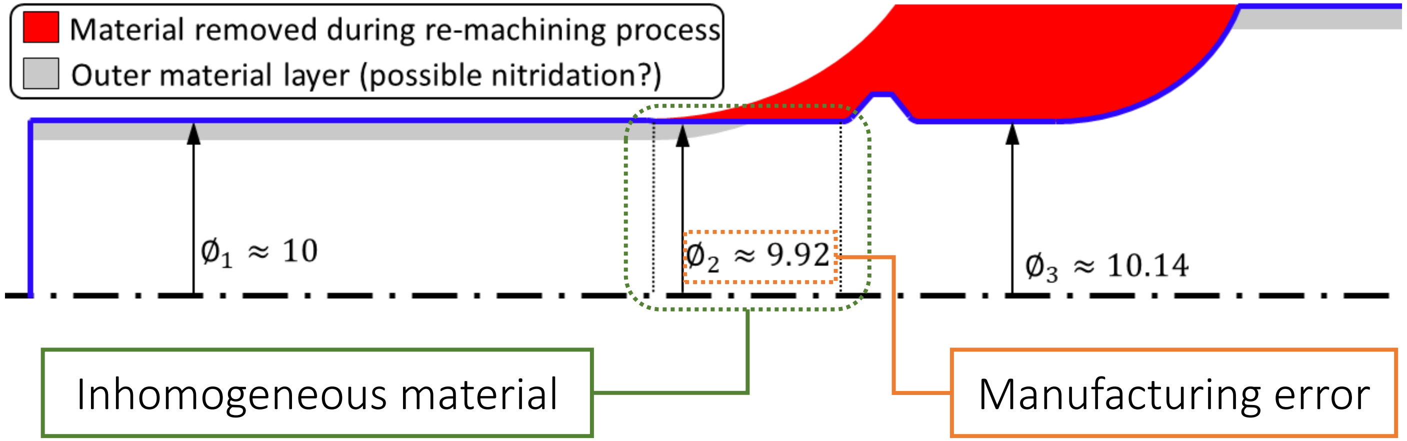


Samples had to be re-machined to include collars for the extensometer grip

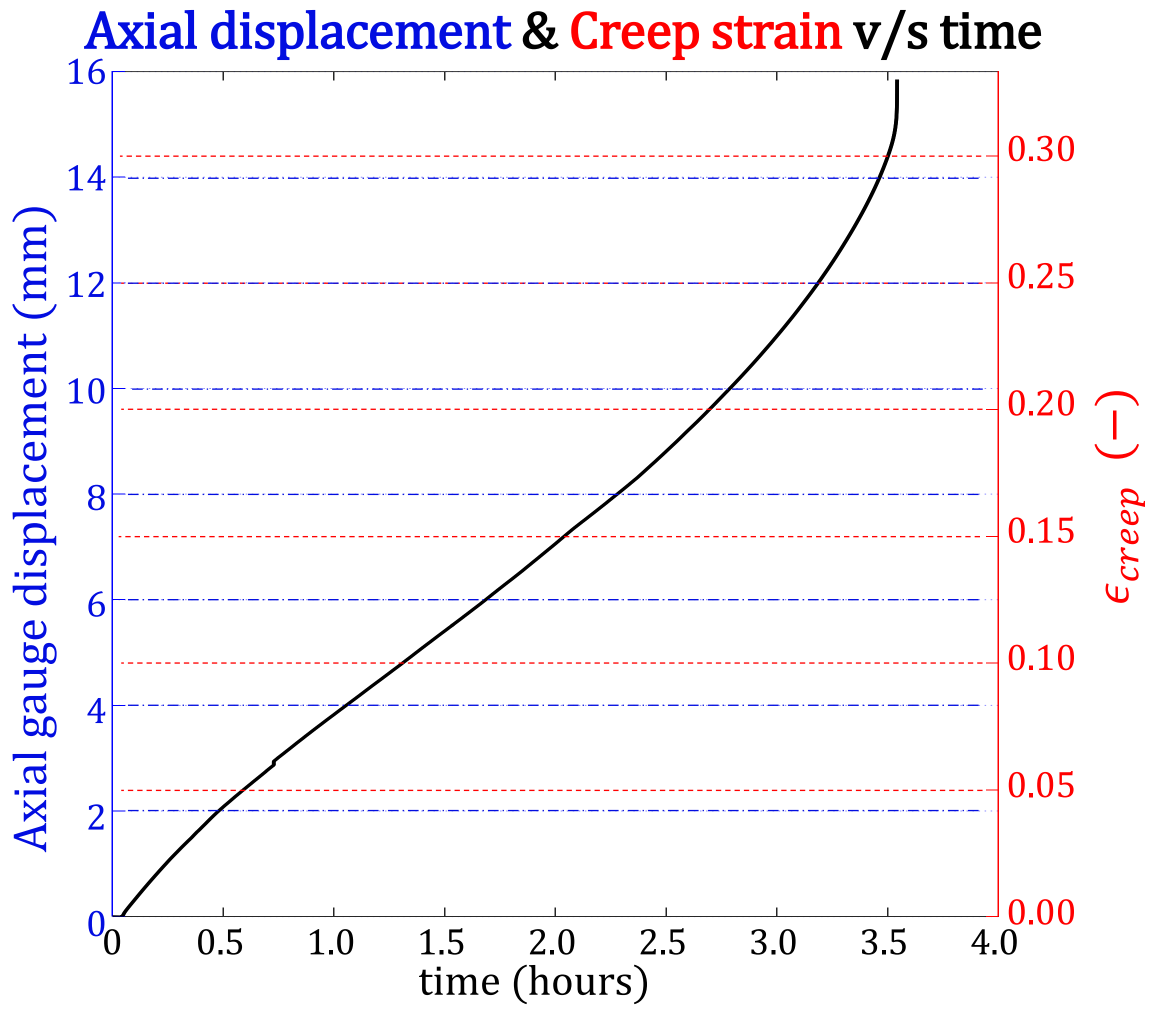
... this is research...

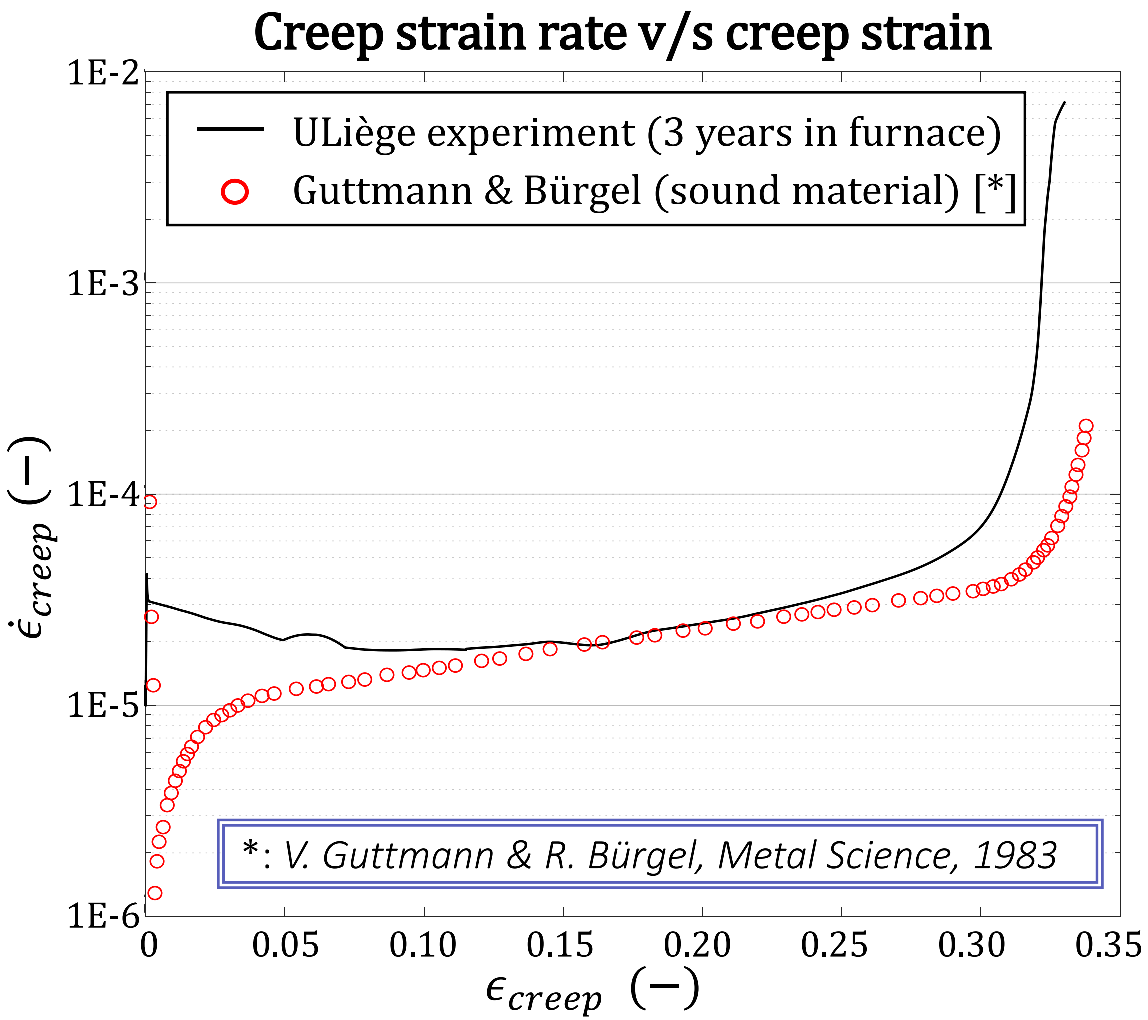
Original planimetry for geometry correction



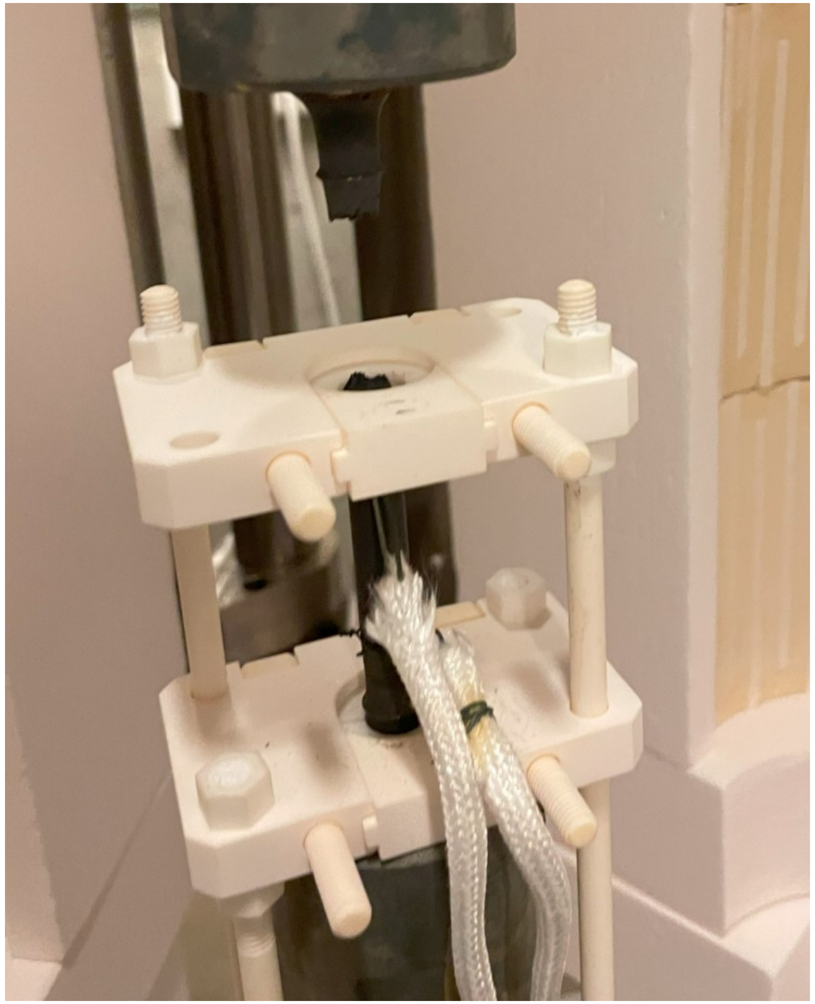


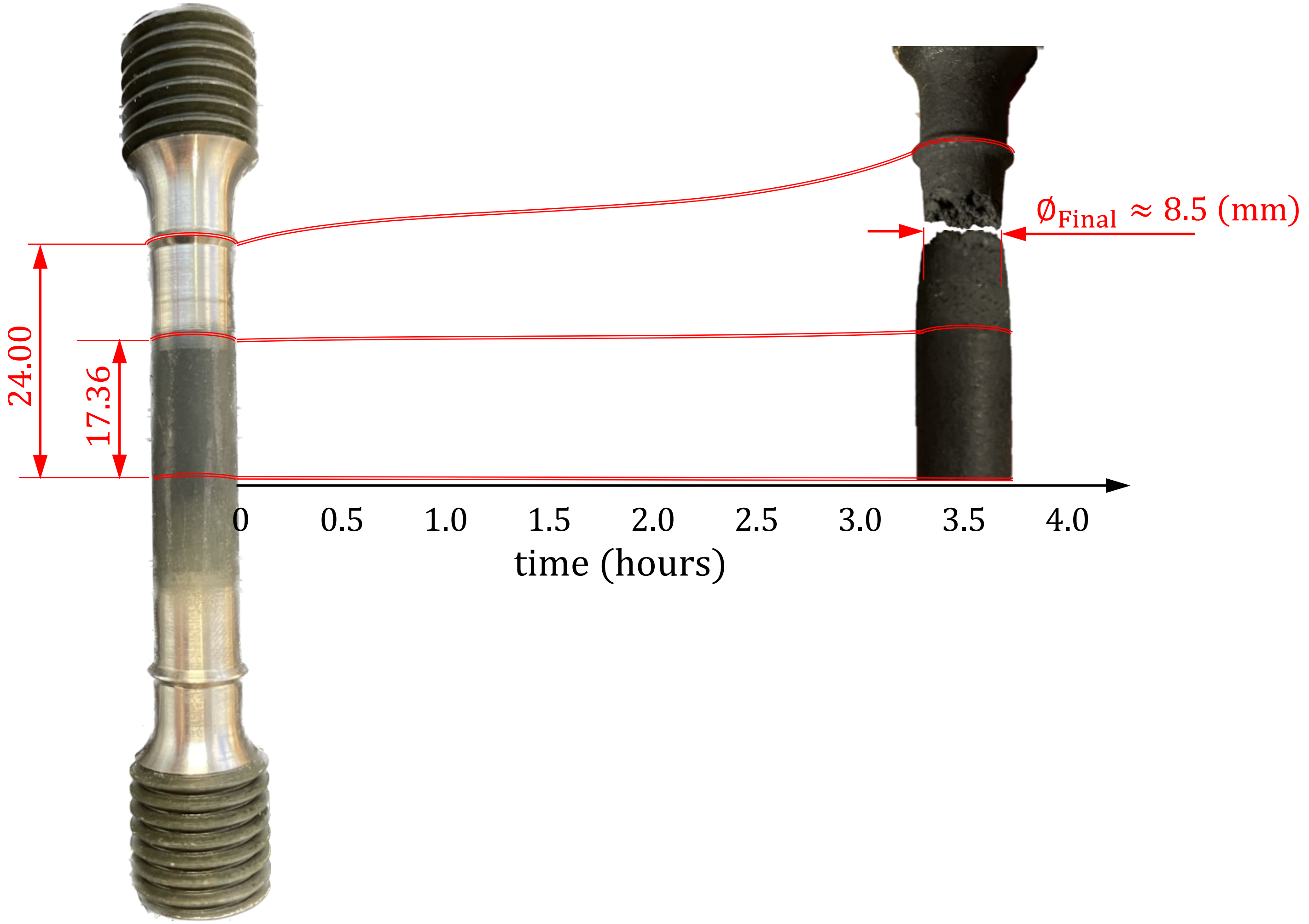
Results for creep test at 1000°C and 35 [MPa] on N3 sample of 800H





Results for creep test at 1000°C and 35 [MPa] on N3 sample of 800H





Yield function: von-Mises criterion

$$f_y = \Sigma_{VM}^{eq} - \sigma_y \le 0$$

$$\underline{\tilde{\boldsymbol{\sigma}}} = (1-D)^{-1}\underline{\boldsymbol{\sigma}}$$ *Effective stress (effect of damage)*

$$\underline{\dot{\mathbf{X}}} = \sum_{i=1}^{n} \underline{\dot{\mathbf{X}}}_{\mathrm{AF},i} + \underline{\dot{\mathbf{X}}}_{\mathrm{SR},i}$$ *Hardening & Static Recovery*

$$\sigma_y = \sigma_0 + Q[1-\exp(-b\cdot\bar{\epsilon}^p)]$$ *Voce isotropic hardening*

Viscoplastic function: Norton power law

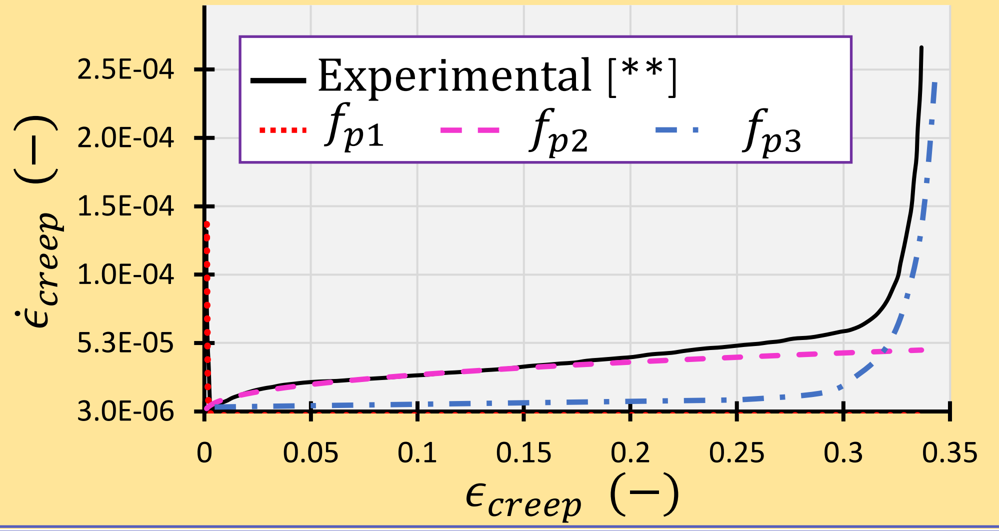
$$\dot{\bar{\epsilon}^p} = \left\langle \frac{f_y}{K} \right\rangle^N \Longleftrightarrow f_y = J_2(\underline{\tilde{\boldsymbol{\sigma}}} - \underline{\mathbf{X}}) - \sigma_y - K(\dot{\bar{\epsilon}^p})^{1/N} \le 0$$

Viscoplastic function: Graham-Walles approach [*]

$$\dot{\bar{\epsilon}^p} = \sum_{j=1}^{vp_i} K_j e^{\frac{\mathrm{T}}{C}} [\Sigma_{VM}^{eq}]^{n_j} (\bar{\epsilon}^p)^{m_j} + K_T \sigma |\dot{\mathrm{T}}| (\bar{\epsilon}^p)^{m_T}$$

$$\dot{\bar{\epsilon}^p} = f_{p1} + f_{p2} + f_{p3} + \cdots + f_{pT}$$

1 Function <—> 1 phenomenon



**: Curve after *V. Guttmann & R. Bürgel, Metal Science, 1983*

Damage function: Graham-Walles approach [*]

$$\dot{D} = \dot{D}_C + \dot{D}_f$$

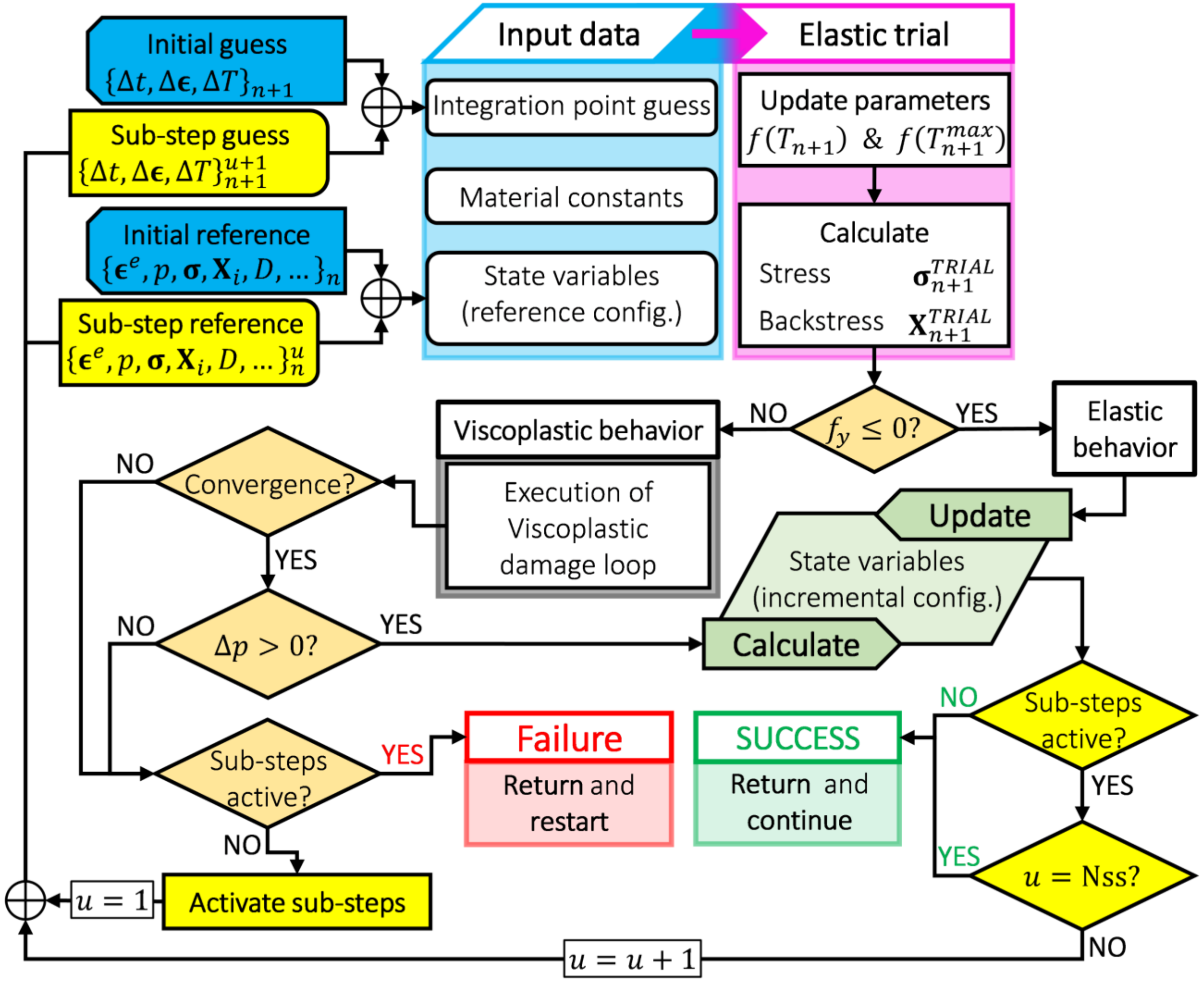
$$\dot{D}_C = K_{TD} |\dot{\mathrm{T}}| (\bar{\epsilon}^p)^{m_{TD}}$$

$$\dot{D}_f = K_D \Sigma_{VM}^{eq}$$

*: Approach after *N.K. Karthik, PhD. Thesis, RWTH Aachen & Darmstadt TU,2016*

Numerical model

Constitutive law integration algorithm [*]



Viscoplastic behaviour:

Fully implicit integration scheme

- Local residual matrix ($\mathbb{R}$)

$$\mathbb{R} = \begin{Bmatrix} \Delta \boldsymbol{\underline{\epsilon}}^e \\ \Delta \bar{\epsilon}^p \\ \Delta \boldsymbol{\underline{\sigma}} \\ \Delta \underline{\mathbf{X}}_i \\ \Delta D \end{Bmatrix} \Longrightarrow \begin{aligned} \Delta \boldsymbol{\underline{\epsilon}}^e &= f(\Delta \bar{\epsilon}^p, \Delta \boldsymbol{\underline{\sigma}}, \Delta \underline{\mathbf{X}}_i, \Delta D) \\ \Delta \bar{\epsilon}^p &= f(\Delta \bar{\epsilon}^p, \Delta \boldsymbol{\underline{\sigma}}, \Delta \underline{\mathbf{X}}_i, \Delta D) \\ \Delta \boldsymbol{\underline{\sigma}} &= f(\Delta \boldsymbol{\underline{\epsilon}}^e, \Delta \boldsymbol{\underline{\sigma}}, \Delta D) \\ \Delta \underline{\mathbf{X}}_i &= f(\Delta \bar{\epsilon}^p, \Delta \boldsymbol{\underline{\sigma}}, \Delta \underline{\mathbf{X}}_i, \Delta D) \\ \Delta D &= f(\Delta \bar{\epsilon}^p, \Delta \boldsymbol{\underline{\sigma}}, \Delta \underline{\mathbf{X}}_i, \Delta D) \end{aligned}$$

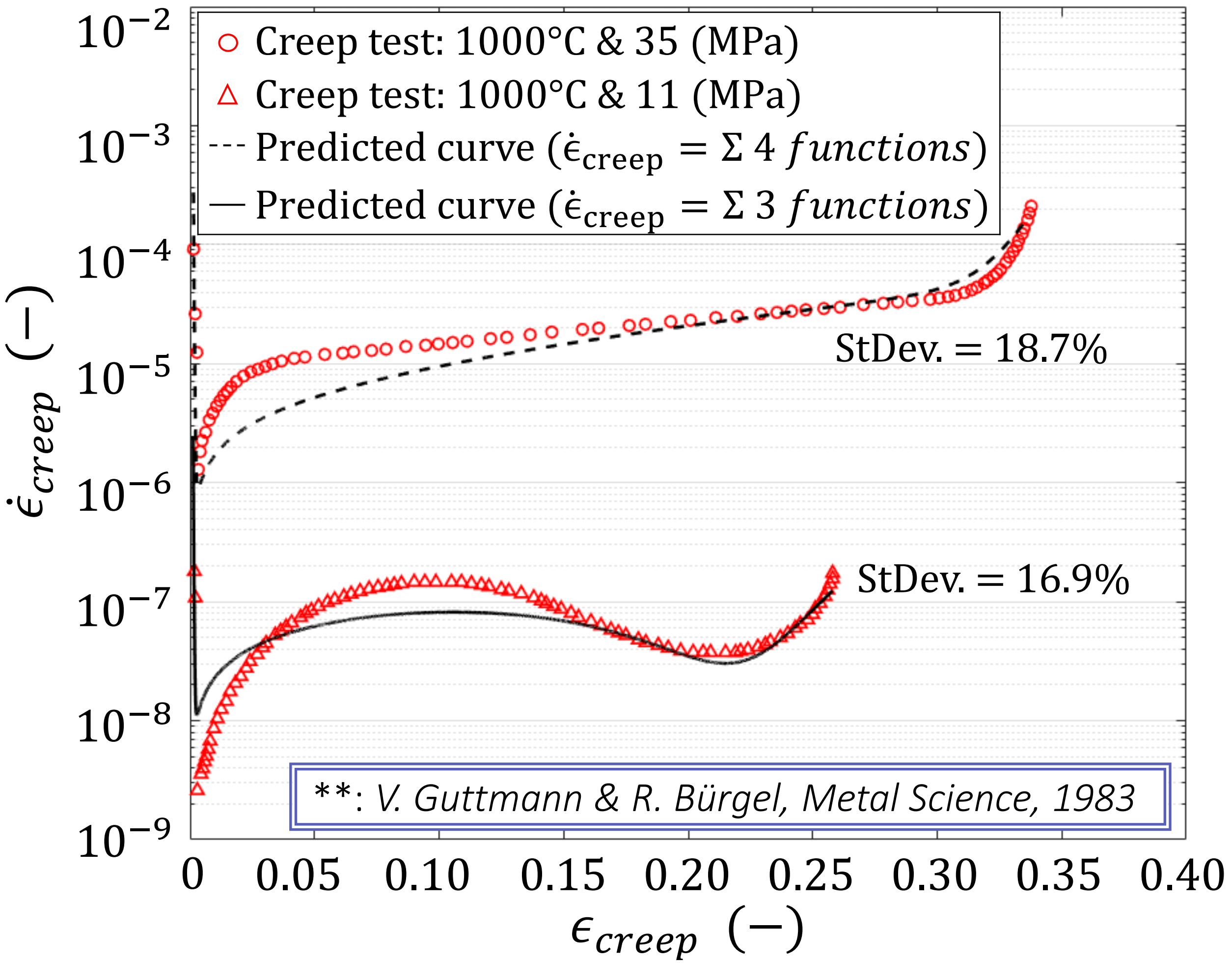
- Radial return mapping algorithm

$$\begin{Bmatrix} \Delta \boldsymbol{\underline{\epsilon}}^e \\ \Delta \bar{\epsilon}^p \\ \Delta \boldsymbol{\underline{\sigma}} \\ \Delta \underline{\mathbf{X}}_i \\ \Delta D \end{Bmatrix}_{n+1}^{k+1} = \begin{Bmatrix} \Delta \boldsymbol{\underline{\epsilon}}^e \\ \Delta \bar{\epsilon}^p \\ \Delta \boldsymbol{\underline{\sigma}} \\ \Delta \underline{\mathbf{X}}_i \\ \Delta D \end{Bmatrix}_{n+1}^{k} - \left[inv(\mathcal{J}\{\underline{R}\}) \cdot \underline{R} \right]_{n+1}^{k}$$

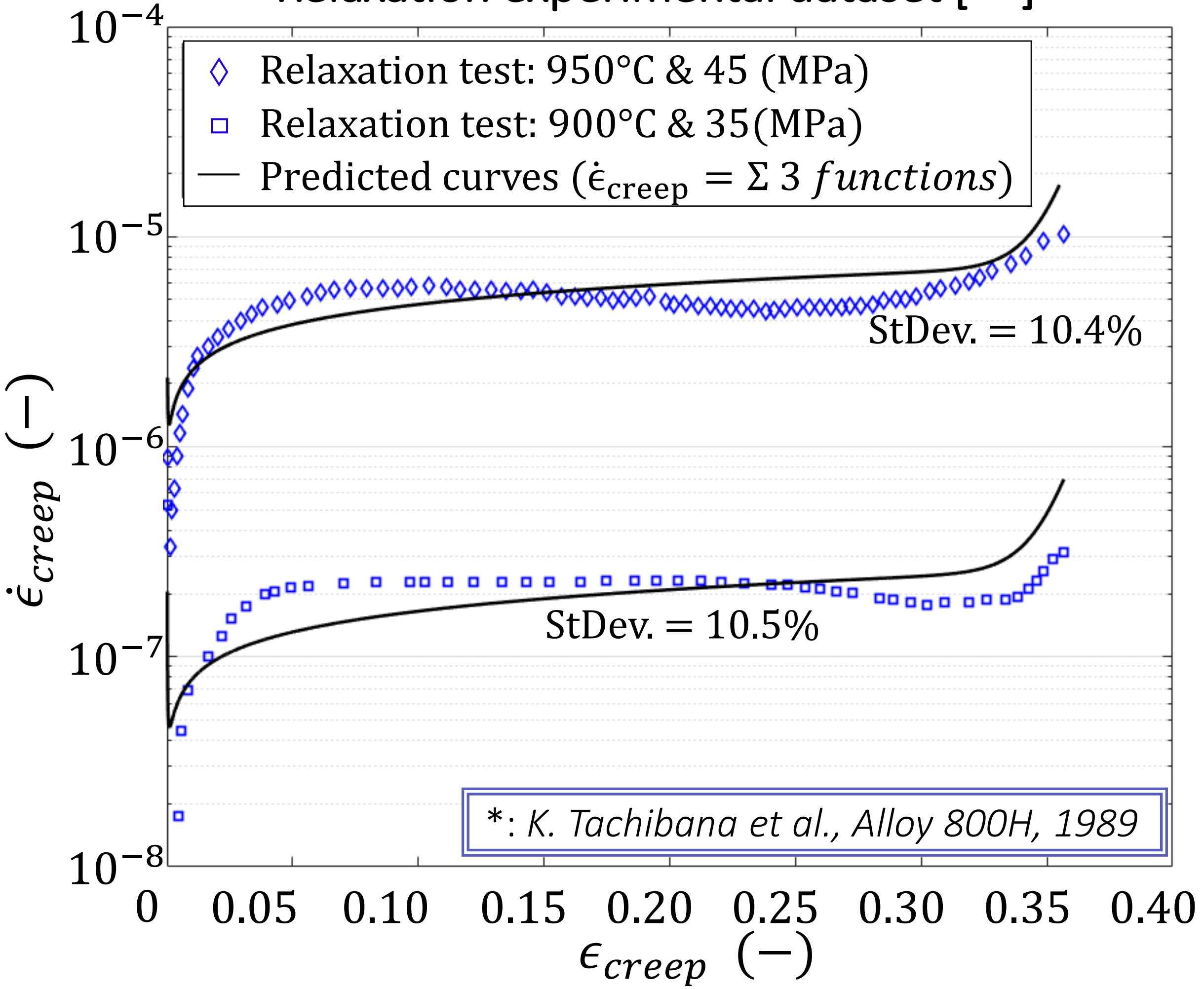
*: Details in *C. Rojas-Ulloa et al., Comput. Math. With Appl., 2023?*

Validation of the Chaboche-type + Graham-Walles viscoplastic function | **1 Finite Element**

Creep experimental dataset [*]

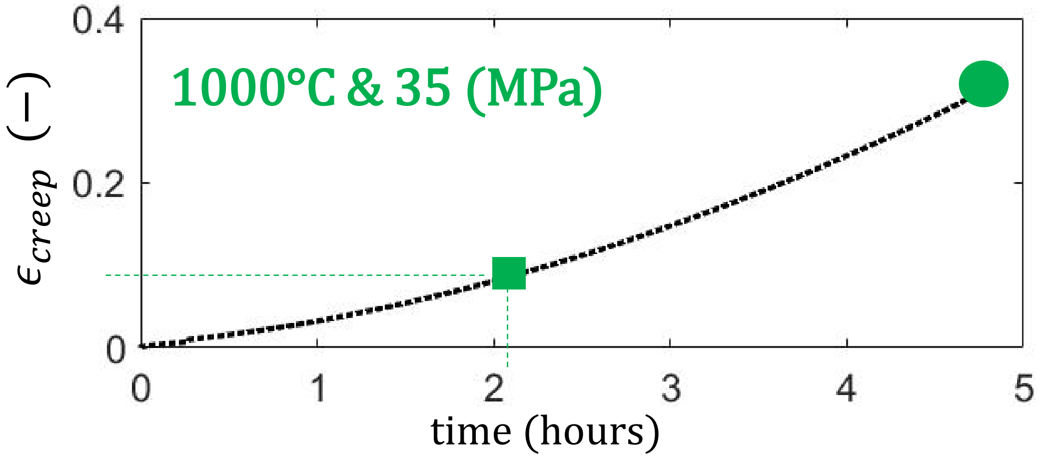


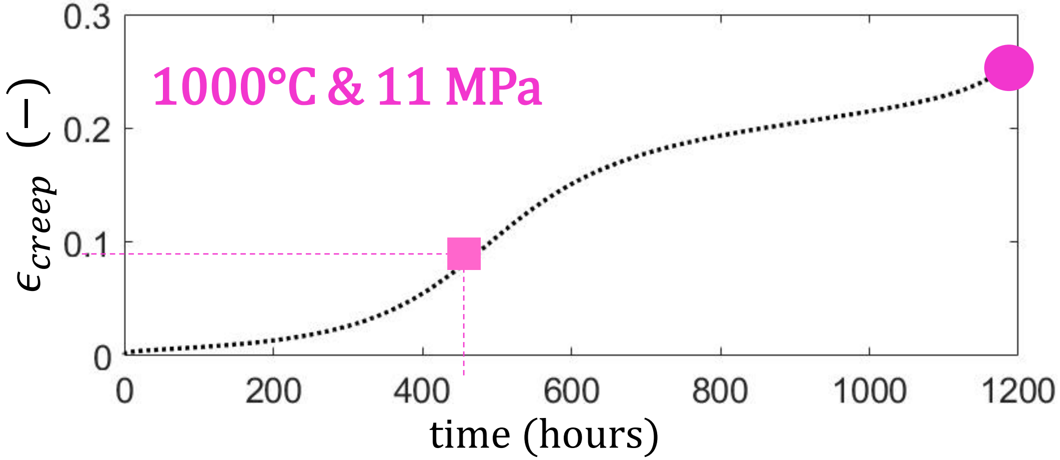
Relaxation experimental dataset [**]



Validation of the Chaboche-type + Graham-Walles viscoplastic function | **1 Finite Element**

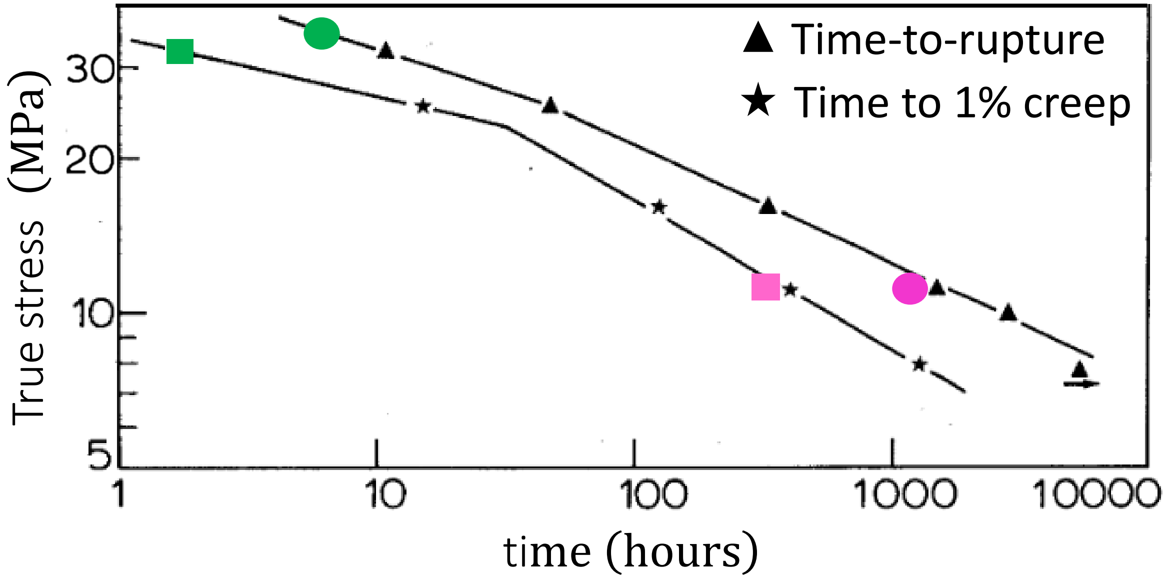
Numerical creep v/s time curves for 800H [*]





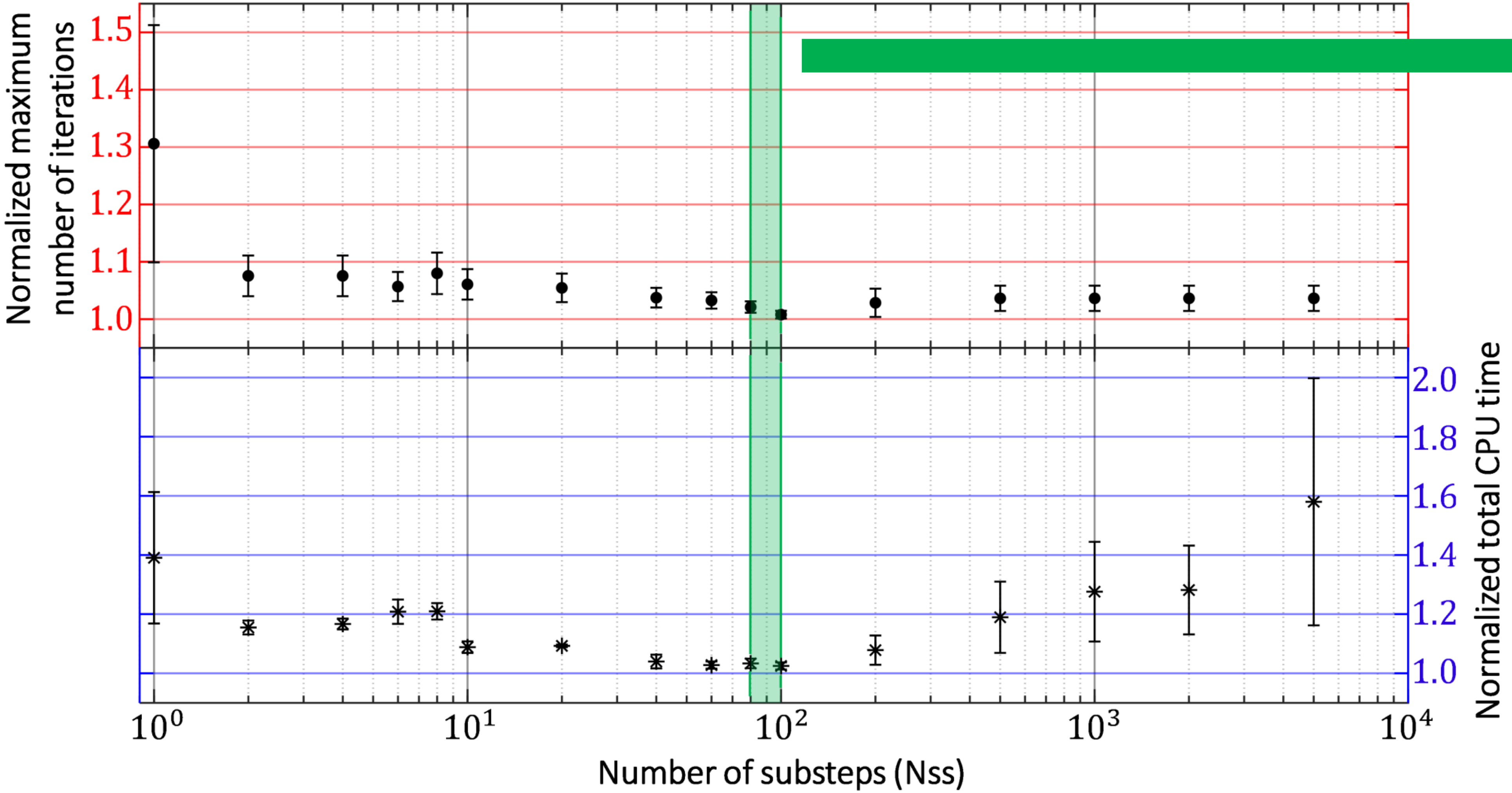
- Results are found within experimental limits

Creep rupture strength & time-to-1% creep [*]



*: *V. Guttmann & R. Bürgel, Metal Science, 1983*

Assessment of computational efficiency| **1 Finite Element**

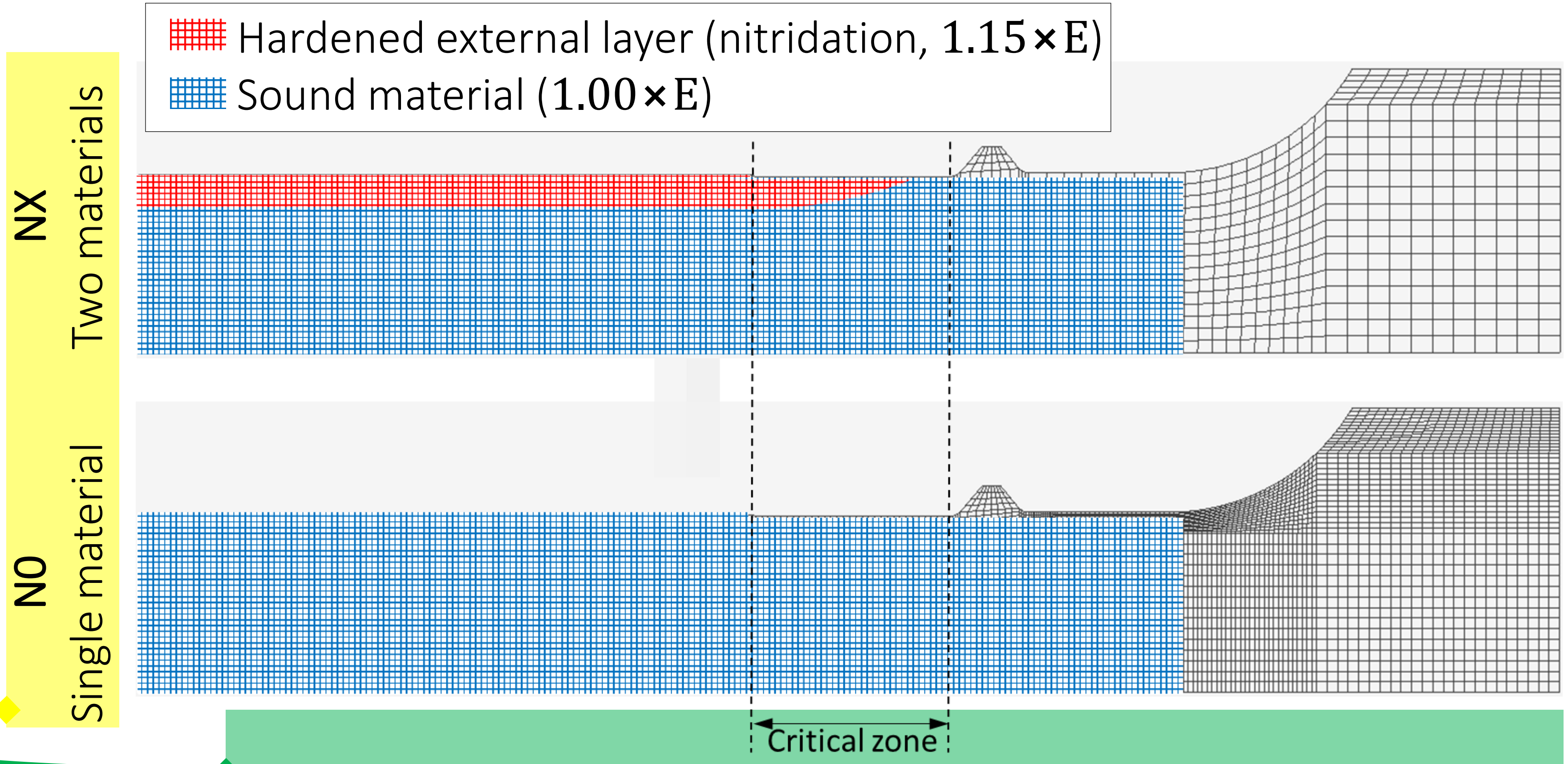


Optimal Nss

❖ Why did our samples failed this way?

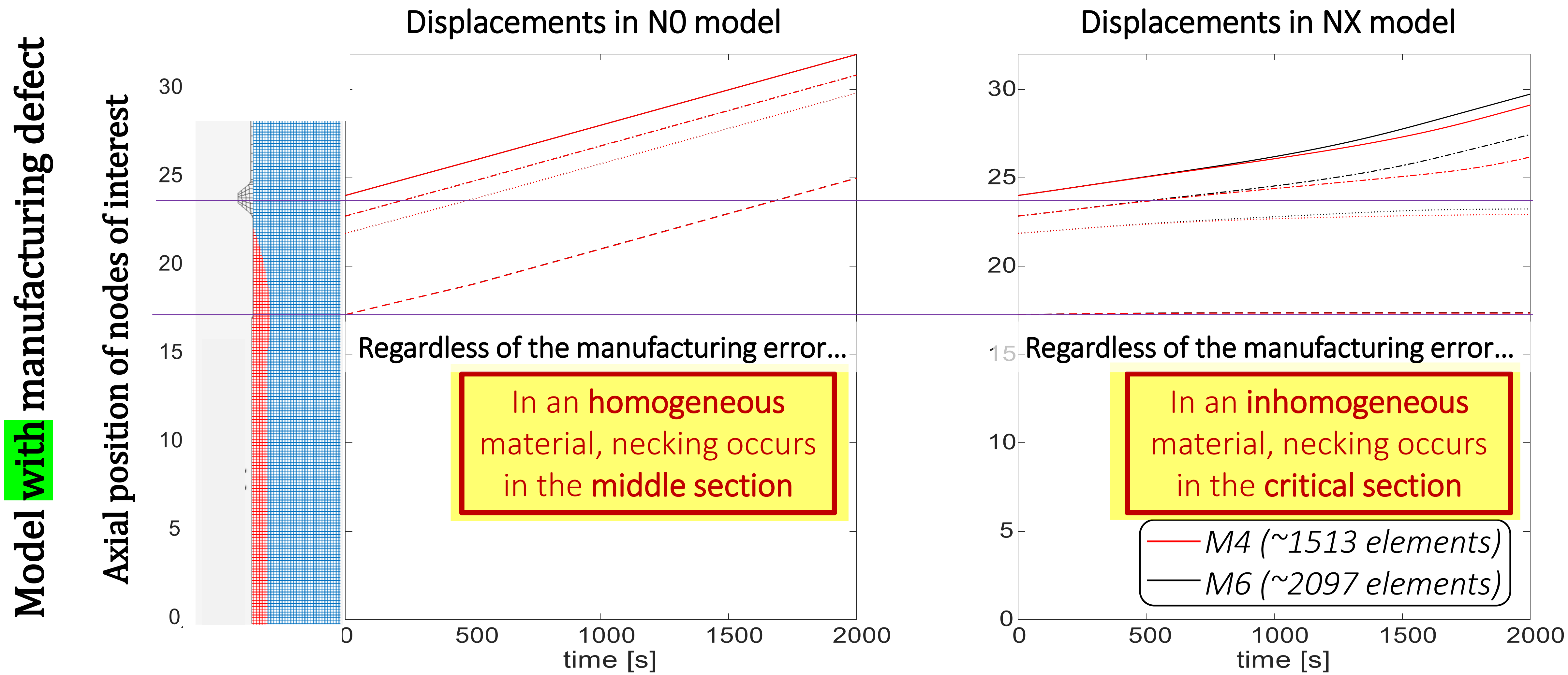
Two theories were addressed:

- Material inhomogeneity
- Manufacturing defect



$\varnothing_{ideal} = 10\ (mm)$ | $\varnothing_{real} = 9.92\ (mm)$

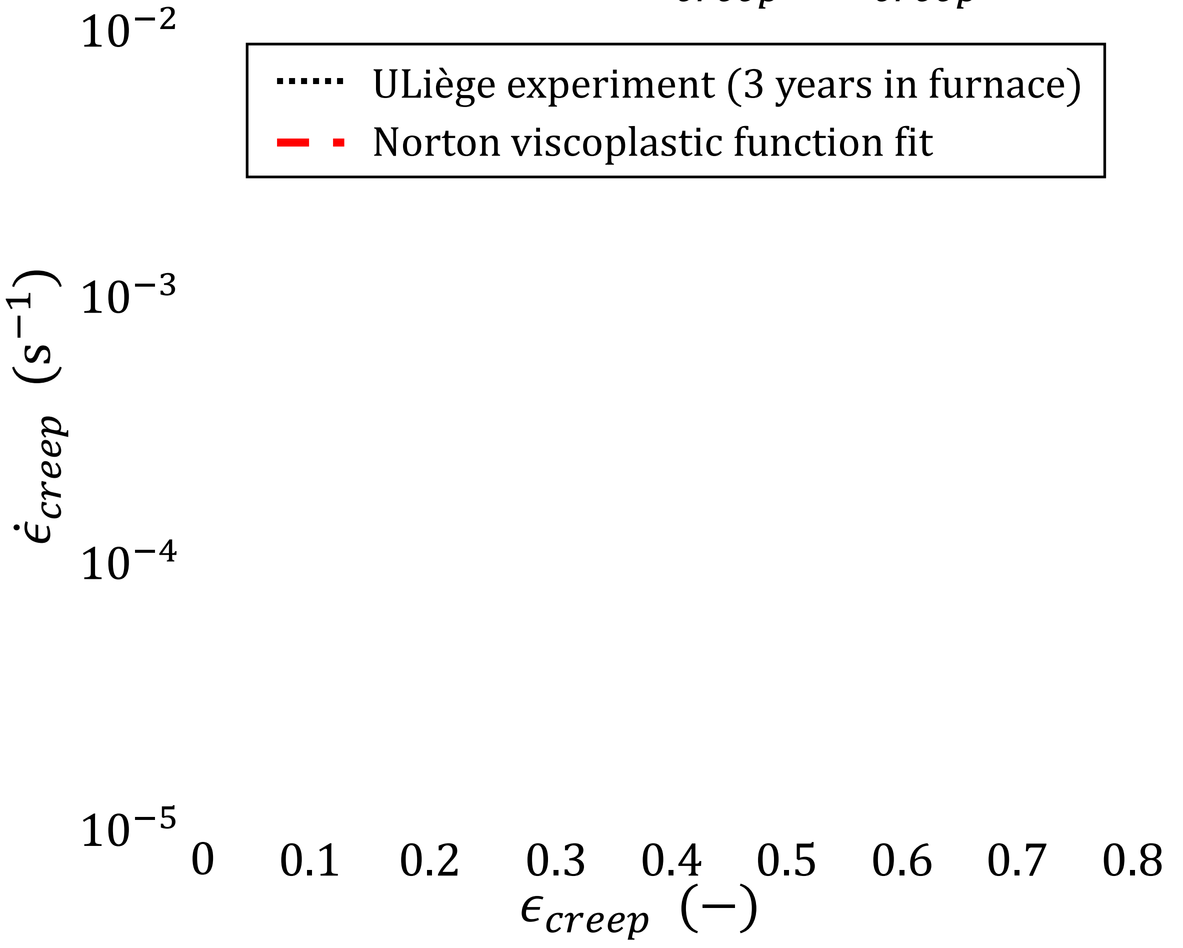
Stage 1: 2D analysis | Hot quasi-static tensile test | simple elastoplastic law



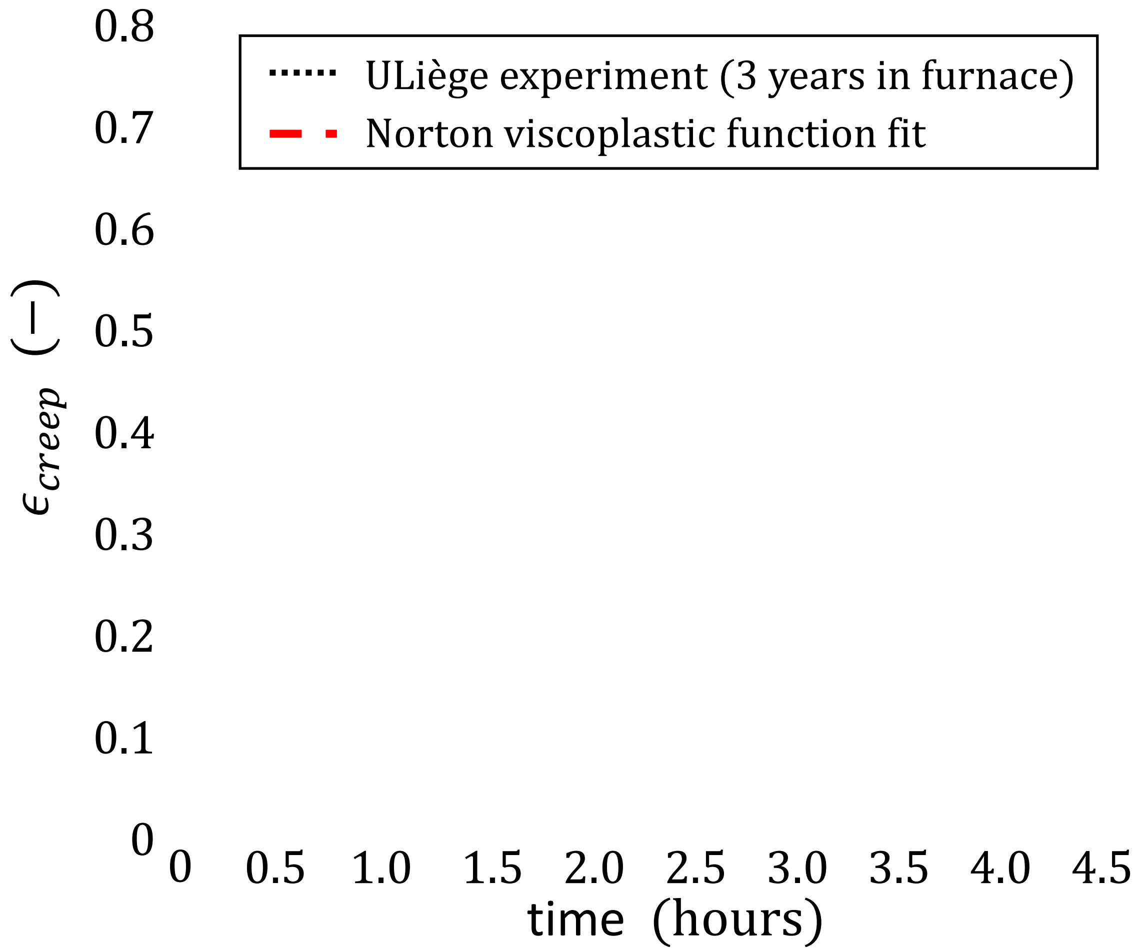
Methodology

Stage 2: 3D analysis | Chaboche-type colaw | Norton-Hoff viscoplastic function

Norton function fit on $\dot{\epsilon}_{creep} - \epsilon_{creep}$ curves



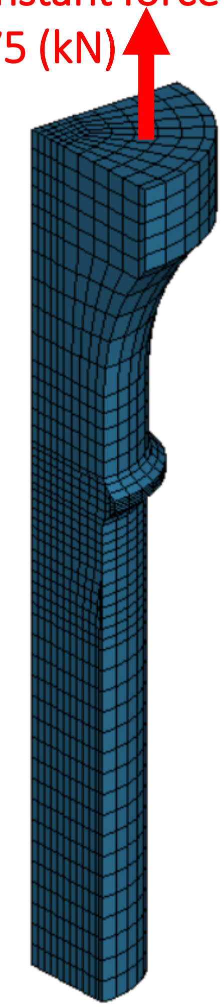
Norton function fit on $\epsilon_{creep} - time$ curves



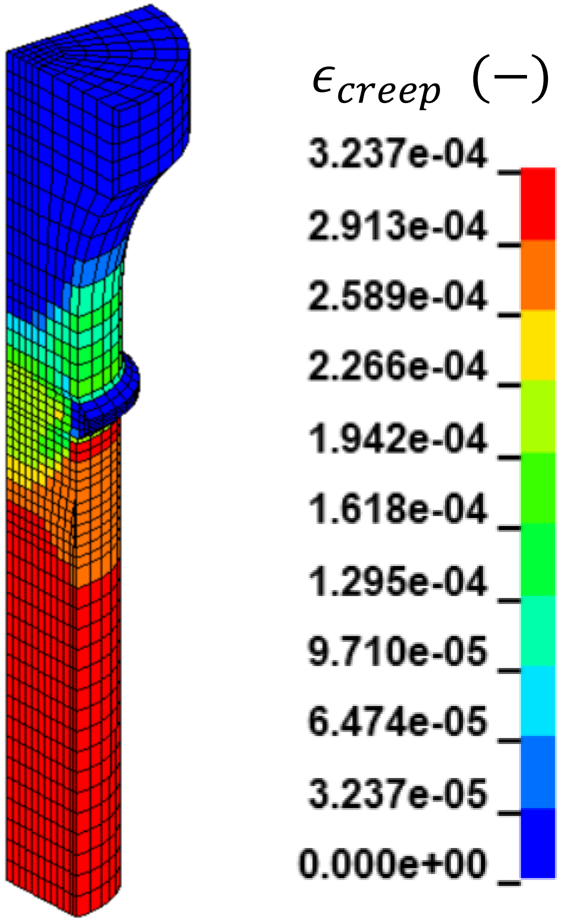
Stage 2: 3D analysis | Chaboche-type colaw | "identified" NH parameters

Model without manufacturing defect

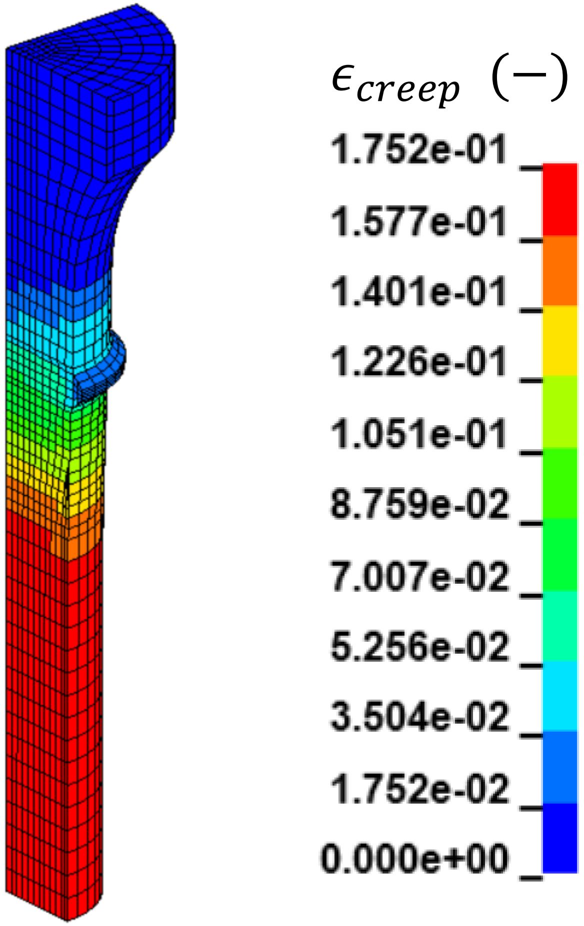
Constant force
2.75 (kN)



Start of viscoplasticity (total load applied)



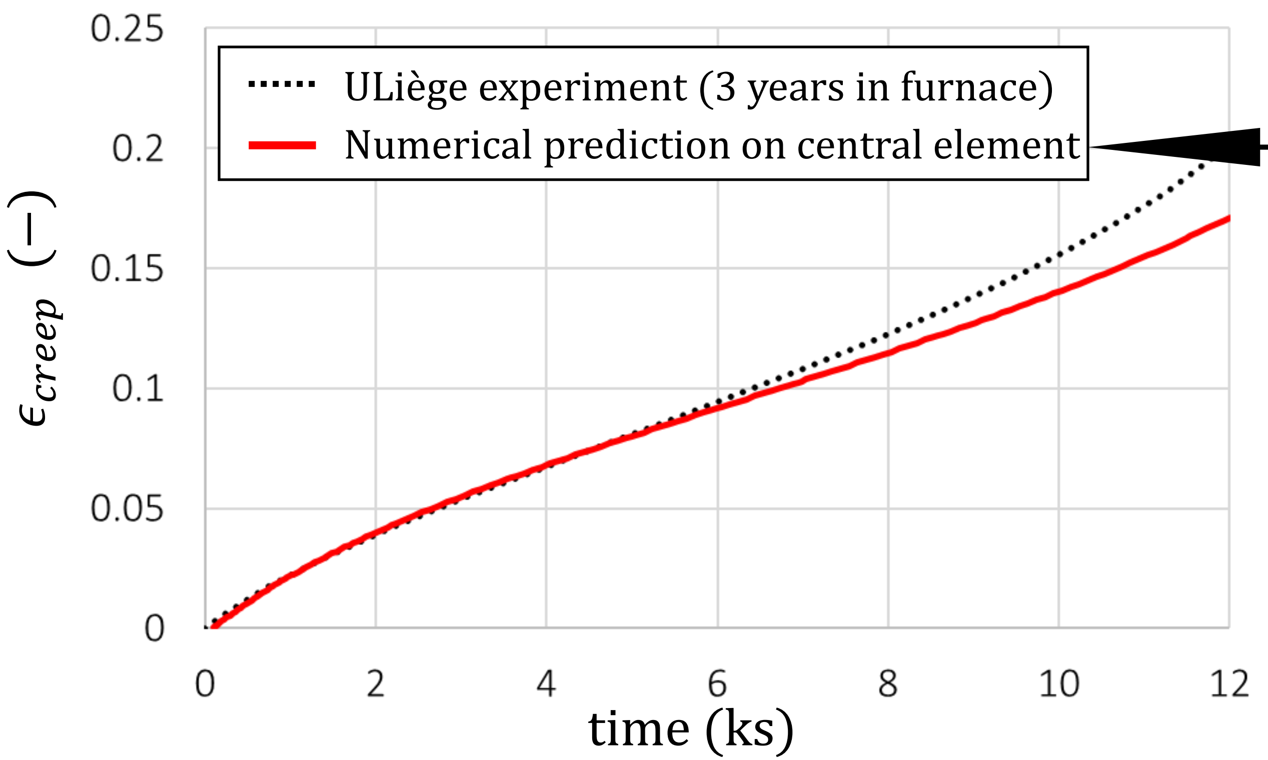
End of test -> time = 12k (s) ≈3.33 (hours)



Stage 2: 3D analysis | Chaboche-type colaw | "identified" NH parameters

Model without manufacturing defect

Experimental v/s numerical $\epsilon_{creep} - time$ curve



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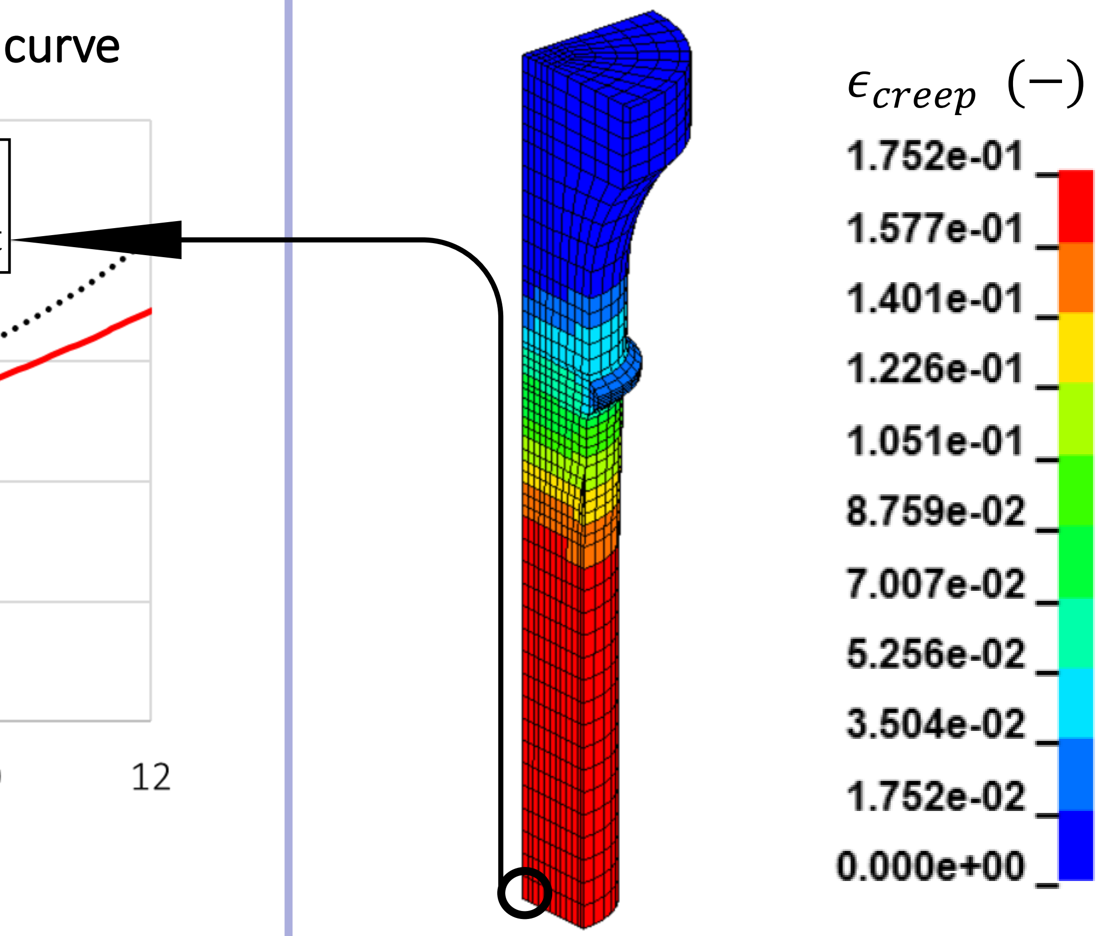
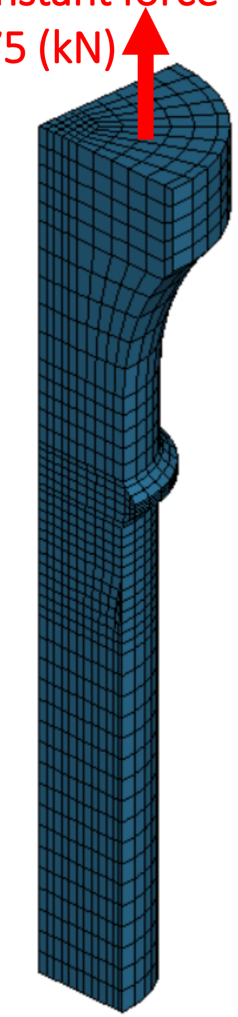
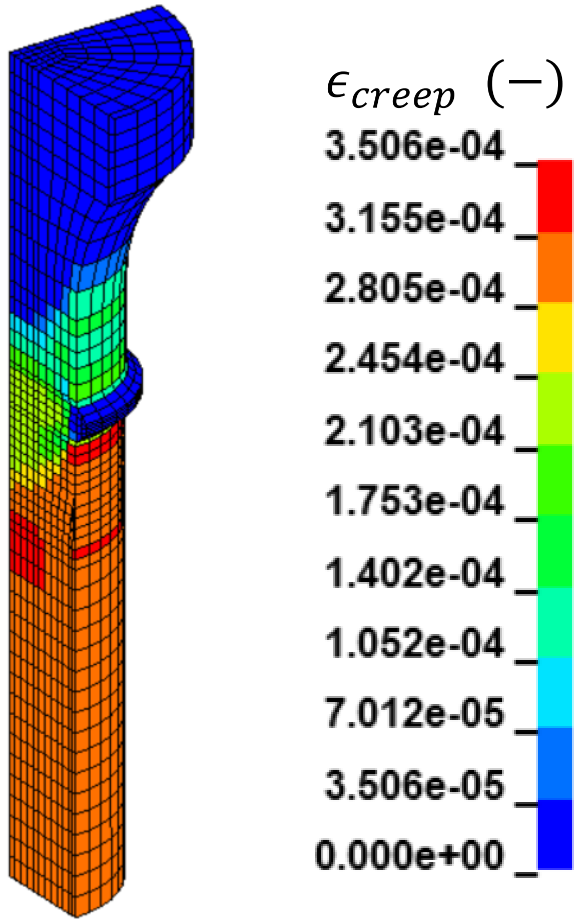


Stage 2: 3D analysis | Chaboche-type colaw | “identified” NH parameters

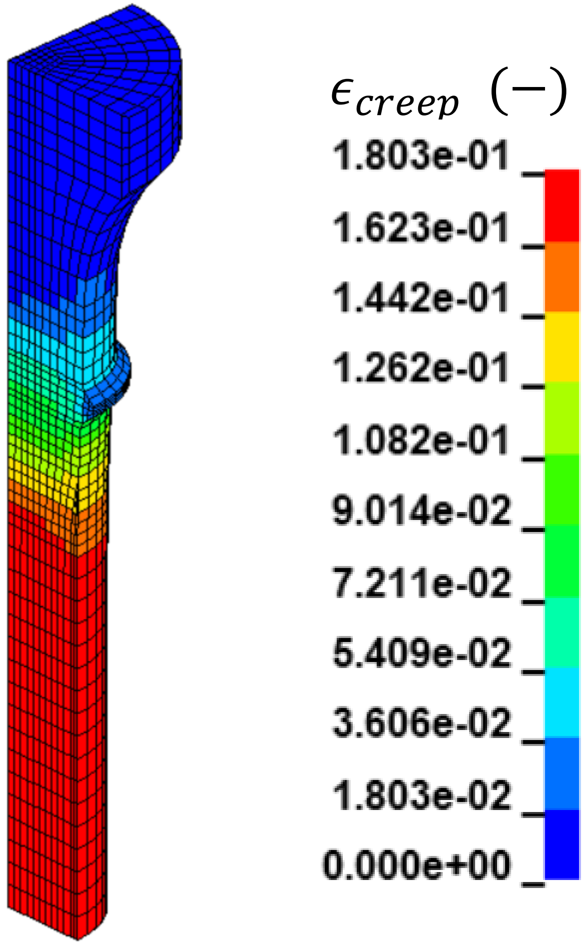
Model with manufacturing defect



Start of viscoplasticity (total load applied)



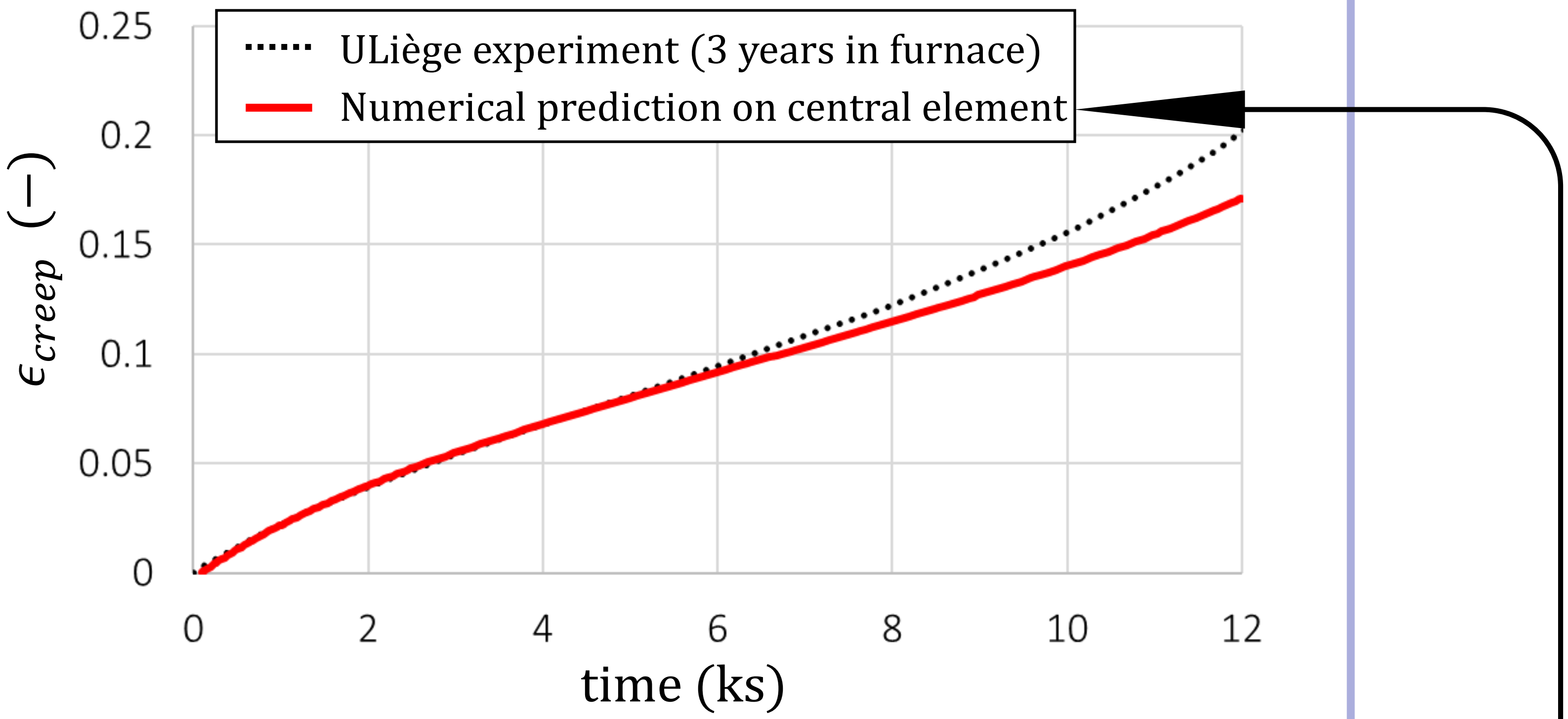
End of test -> time = 12k (s) ≈3.33 (hours)



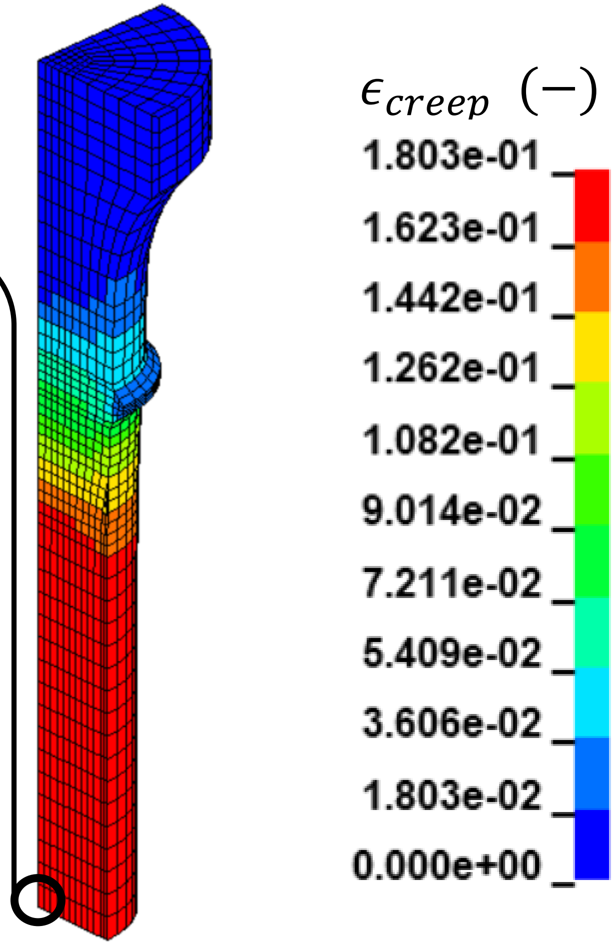
Stage 2: 3D analysis | Chaboche-type colaw | “identified” NH parameters

Model with manufacturing defect

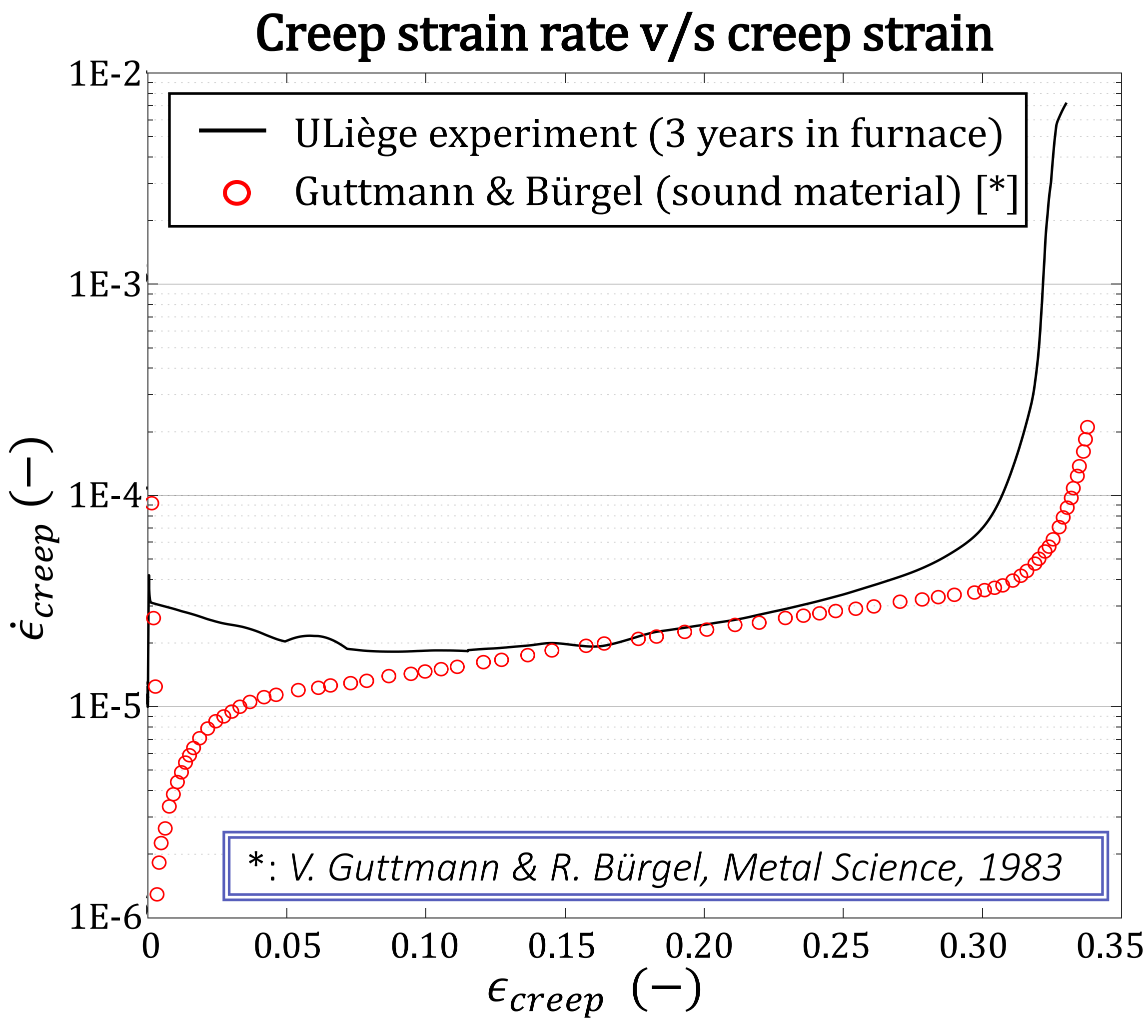
Experimental v/s numerical $\epsilon_{creep} - time$ curve



End of test -> time = 12k (s) ≈3.33 (hours)



On our experimental campaign



EP simulations suggest effect of material inhomogeneity

EVP simulations could not predict necking in critical zone

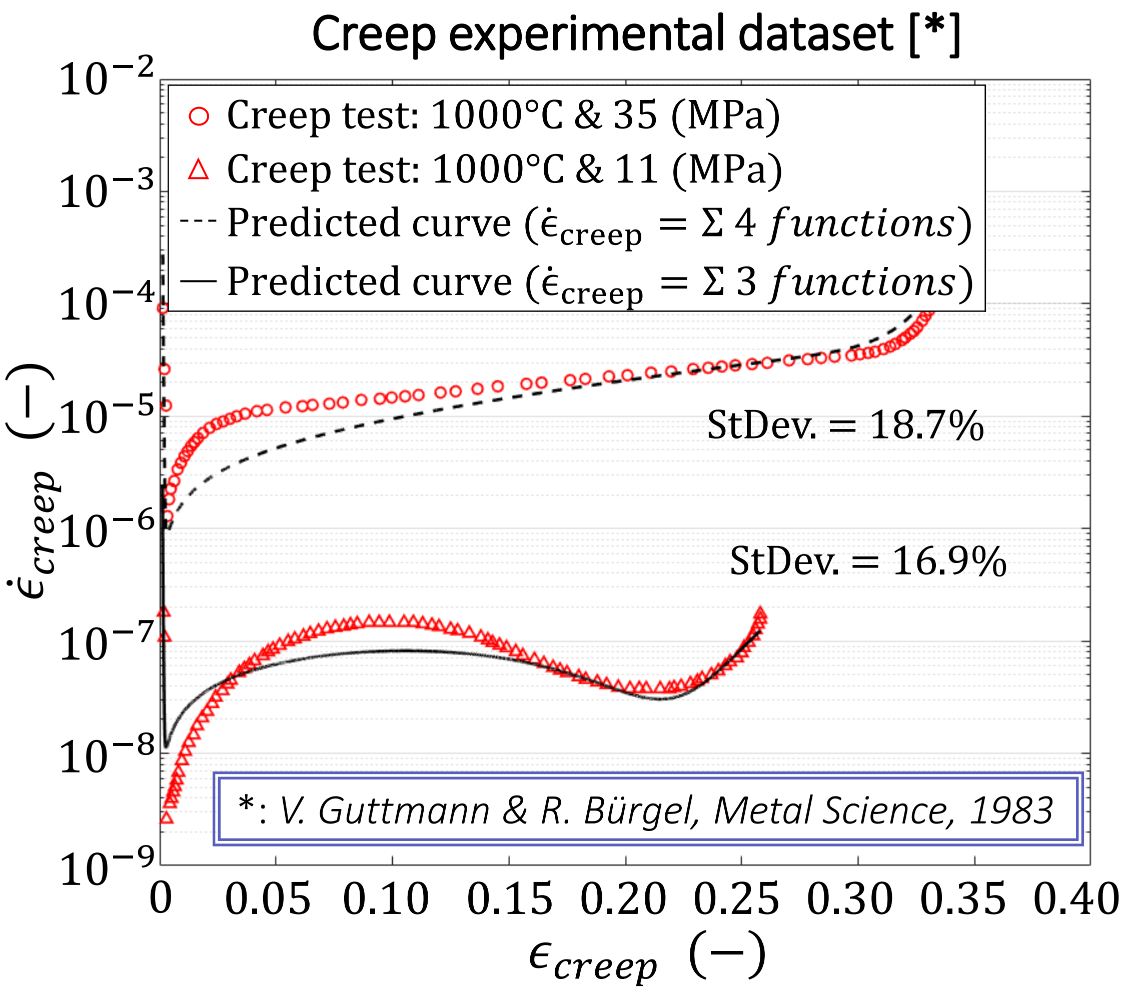
Microstructural evolution of 800H after 3 years in furnace consists in:

- Nitridation/oxidation competition
- Intergranular precipitation of $M_{23}C_6$ carbides

To inquire on the **effect** of **material inhomogeneity** and **microstructure evolution** on the creep behaviour of 800H:

- ➢ Surface mapping via **nanoindentation** on **more samples**
- ➢ Pursue a **thorough experimental campaign**
- ➢ Perform **simulations addressing material inhomogeneity**

On the numerical aspects of the project



The numerical model implemented exhibits **good adaptability for addressing classical & non-classical creep behaviour**

There is still a high uncertainty on the evolution of 800H microstructure and its effect on the creep behaviour

Microstructural evolution of 800H after 3 years in furnace consists in:

- Nitridation/oxidation competition
- Intergranular precipitation of $M_{23}C_6$ carbides

To develop a creep micromechanics approach

- **Coupled** to our macromechanical model
- **Decrease uncertainty of the model**
- Provide **realistic** and **reliable** simulations

The final objective of my PhD. Project

ECCC 2023

027

LIÈGE université Sciences Appliquées

MSM Materials and Solid Mechanics

Accurate very-high temperature creep-life prediction of Incoloy 800H addressing effects of creep mechanism transition and nitridation

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May 25th, 2023

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Project funded by FRIA grant 4000-8987

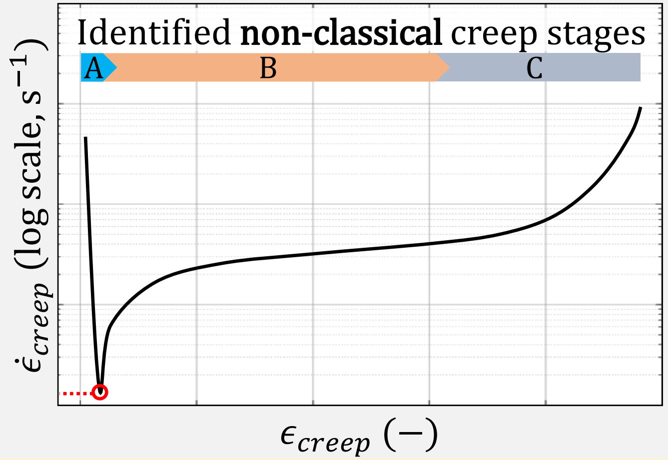
ANNEX: similar behaviour

Creep test

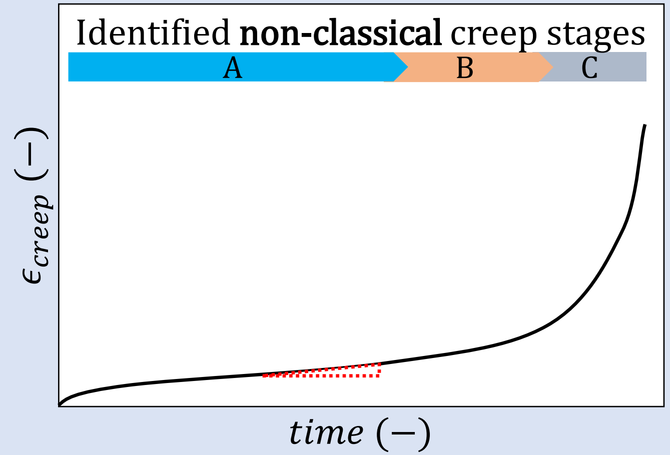
Low **stress** & high T°

Short creep test | inert gas test

Creep strain rate v/s Creep strain

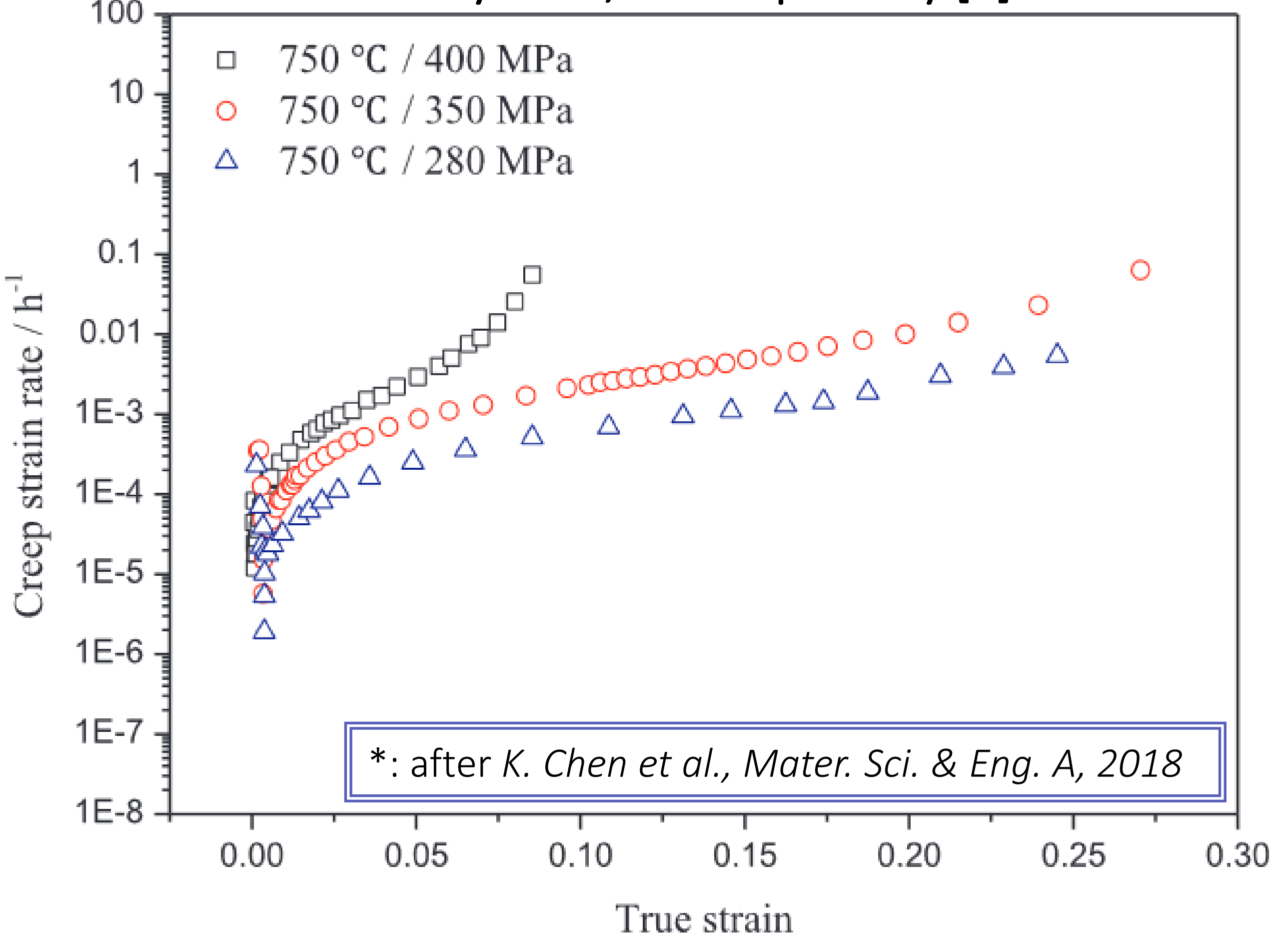


Creep strain v/s time



Similar behaviour has been reported for…

Alloy 718s, a Ni-superalloy [*]



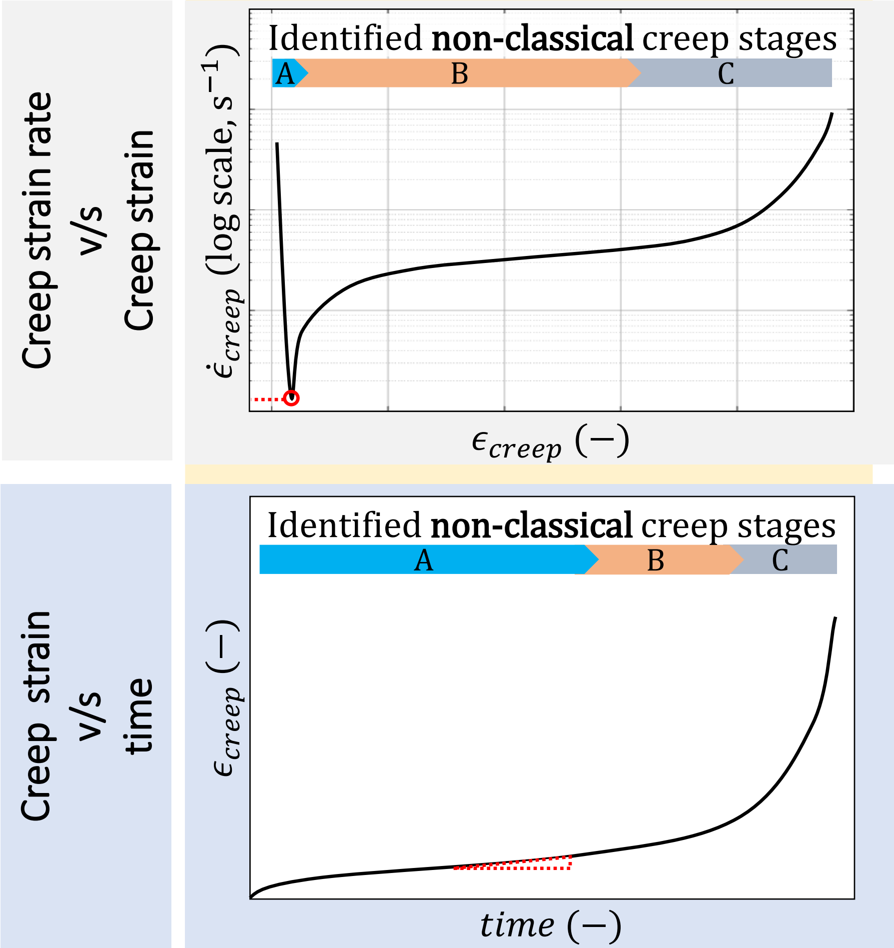
*: after *K. Chen et al., Mater. Sci. & Eng. A, 2018*

ANNEX: similar behaviour

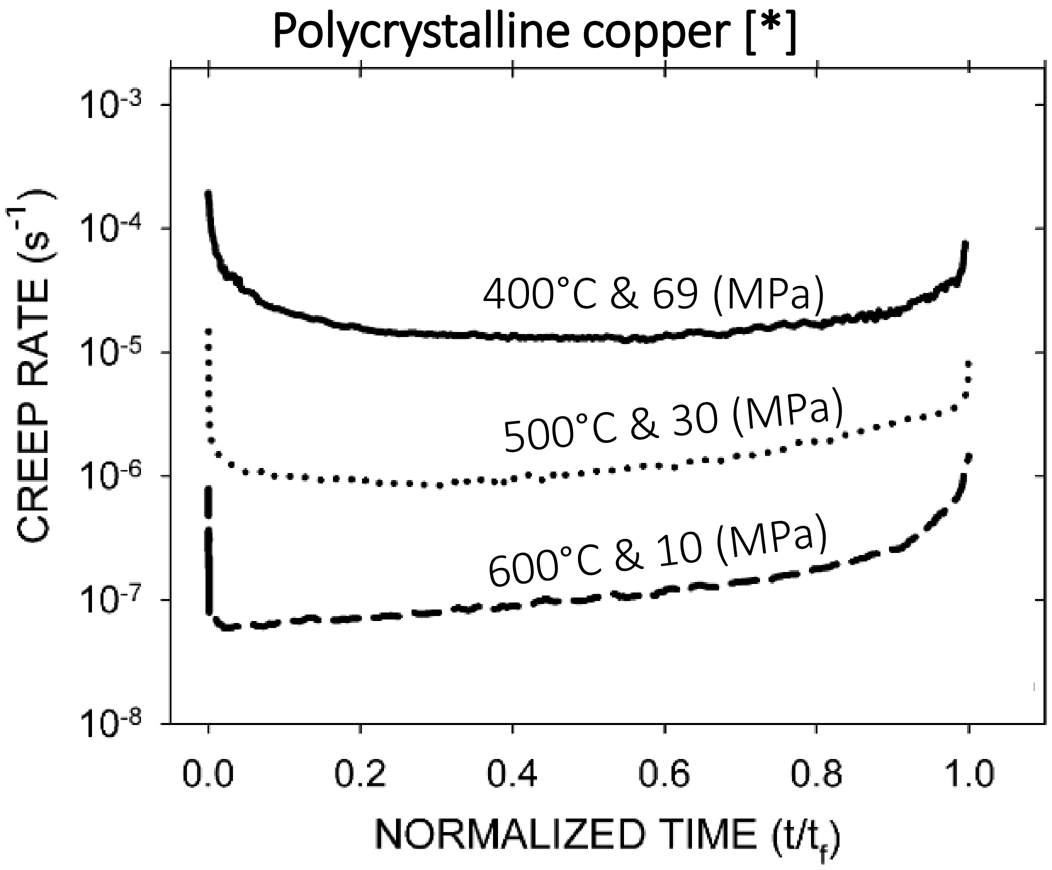
Creep test

Low **stress** & high **T°**

Short creep test | inert gas test



Similar behaviour has been reported for…



*: after *B. Wilshire & A.J. Battenbough, Mater. Sci. & Eng. A, 2007*