LIÈGE université Sciences Appliquées

MSM Materials and Solid Mechanics

Assessment of the influence of creep transition and nitridation in the creep-life prediction of Incoloy 800H

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fnrs LA LIBERTÉ DE CHERCHER **Project funded by FRIA grant 4000-8987**

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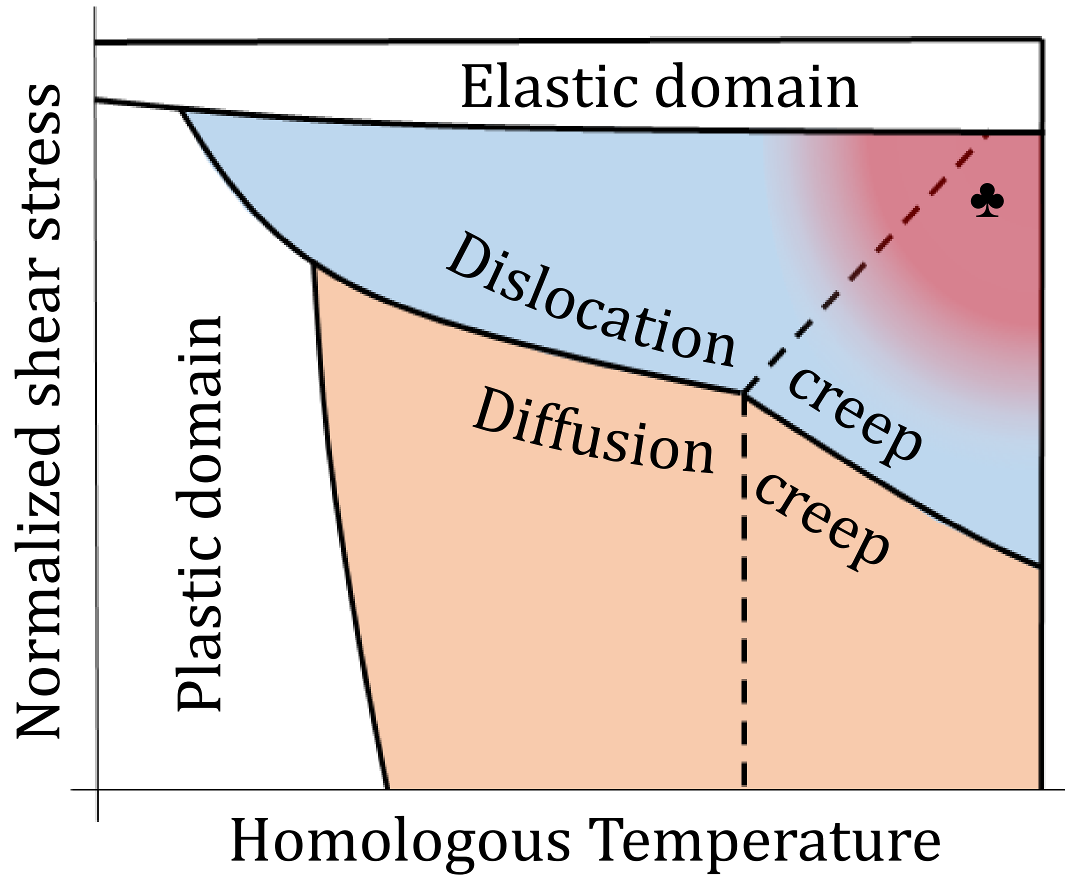
Creep micromechanics

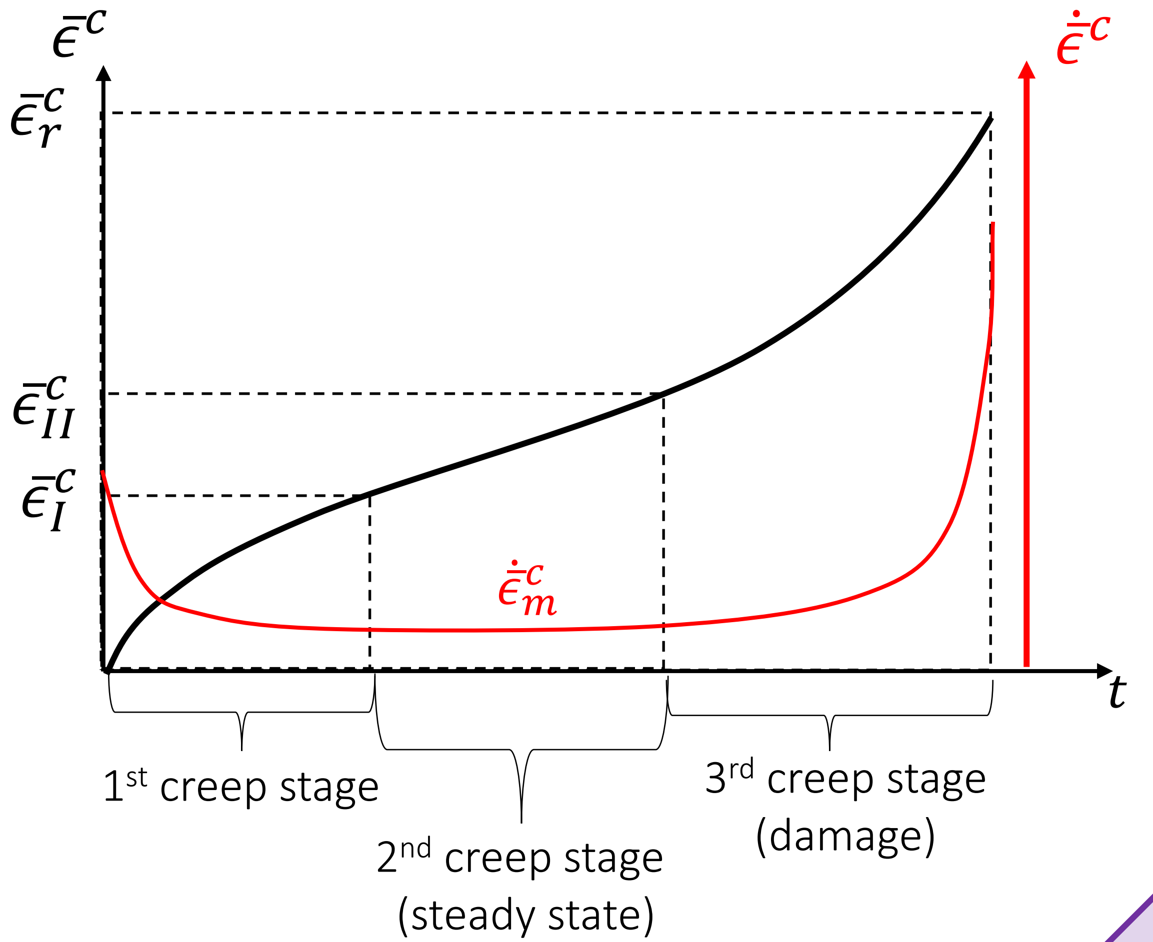
Generic Ashby map



♣: Dynamic recrystallization (DRX)

Creep macromechanics

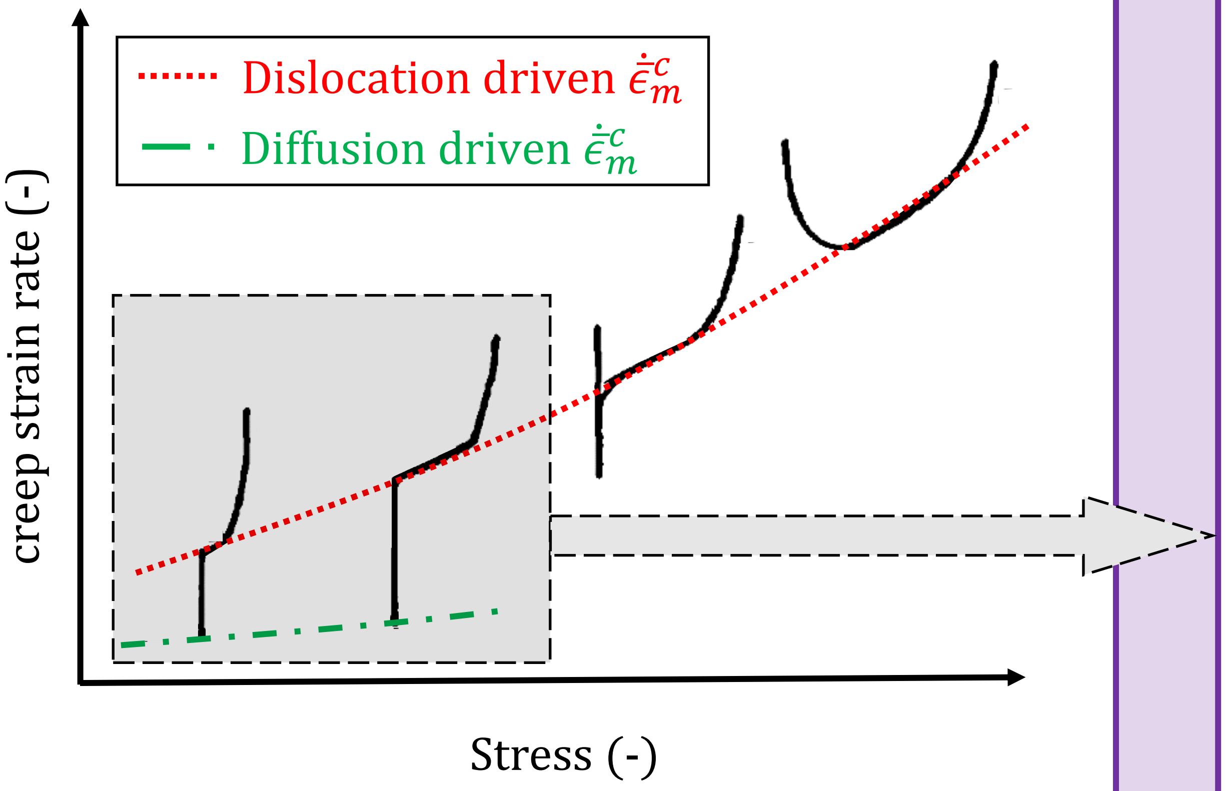
Classical creep ($\bar{\epsilon}^c$) and creep rate ($\dot{\bar{\epsilon}}^c$) vs time curves



Creep in 800H

Qualitative overview

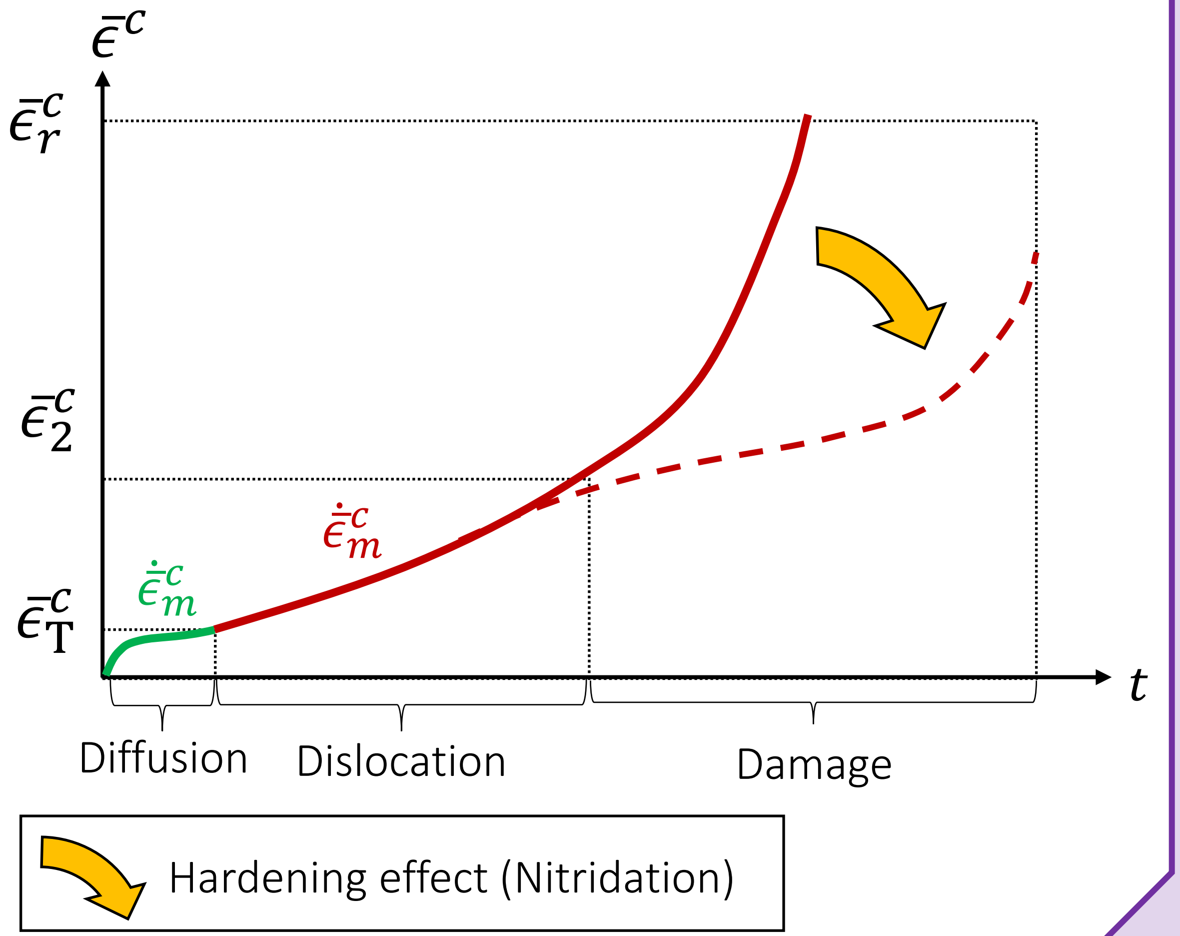
Qualitative depiction of 800H alloy in creep



(Degischer et al., Materials Science, 1989)

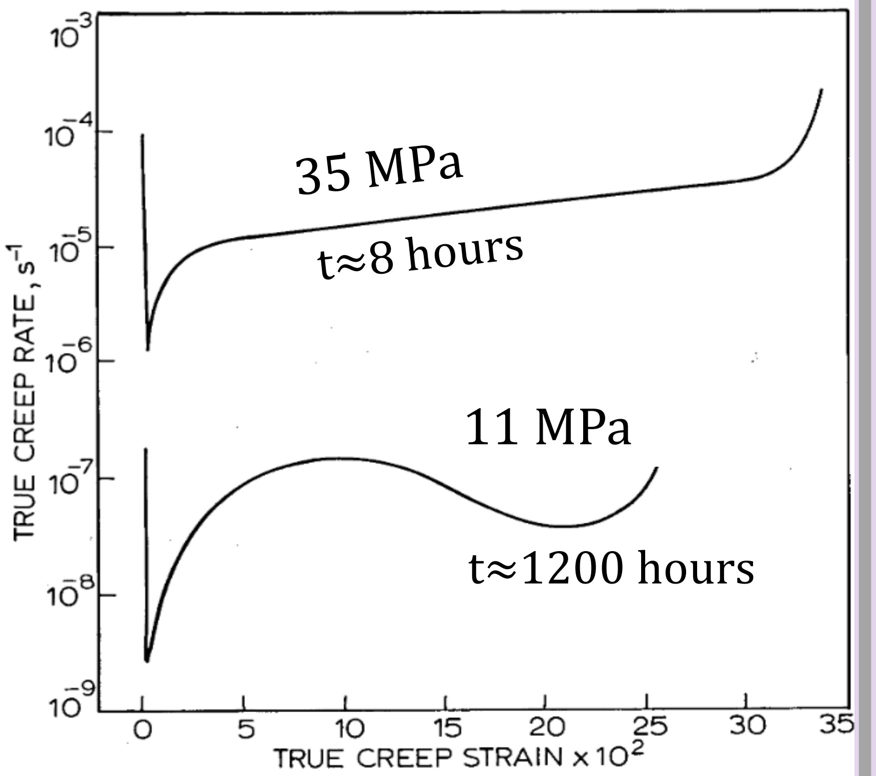
800H creep macromechanics

800H creep ($\bar{\epsilon}^c$) vs time curves



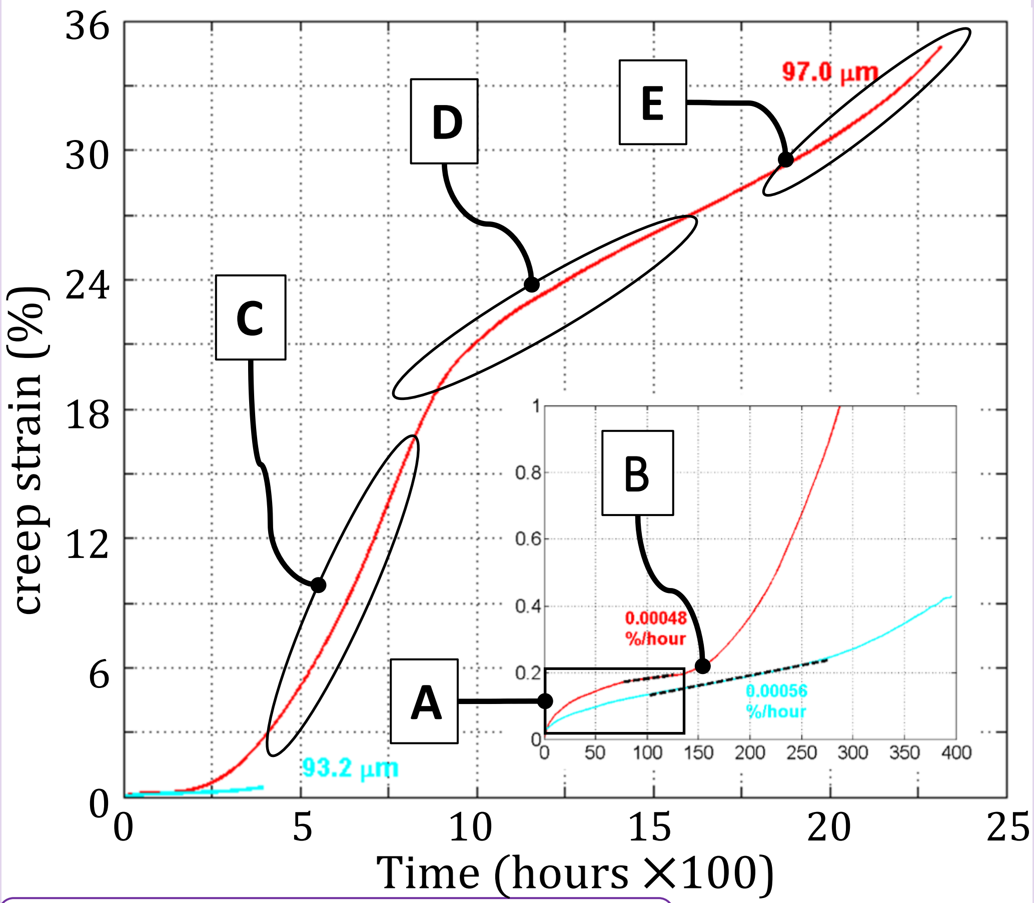
A numerical model to predict the creep-fatigue behavior of 800H:

800H creep in air at 1000°C



(Guttmann & Bürgel, Metal Science, 1983)

800H creep in air at 980°C and 13.8 [MPa]



(B. Gardiner, PhD. thesis, 2014)

A Diffusion - driven creep stage

B Diffusion-dislocation creep transition

C Dislocation - driven creep

D Nitridation-induced creep hardening

E Large tertiary creep (damage accumulation)

Formulation

- Yield function: **von-Mises** criterion

$$f_y = J_2(\underline{\tilde{\boldsymbol{\sigma}}} - \underline{\mathbf{X}}) - \sigma_y \leq 0$$

$$J_2(\underline{\tilde{\boldsymbol{\sigma}}} - \underline{\mathbf{X}}) = \Sigma_{VM} = \left[\frac{3}{2}(\underline{\tilde{\boldsymbol{\sigma}}} - \underline{\mathbf{X}})^{\mathrm{d}} : (\underline{\tilde{\boldsymbol{\sigma}}} - \underline{\mathbf{X}})^{\mathrm{d}}\right]^{0.5}$$

where

$$\underline{\tilde{\boldsymbol{\sigma}}} = (1-D)^{-1}\underline{\boldsymbol{\sigma}}$$ *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*

- Viscoplasticity: **Norton**

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

(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)

- Damage:

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

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

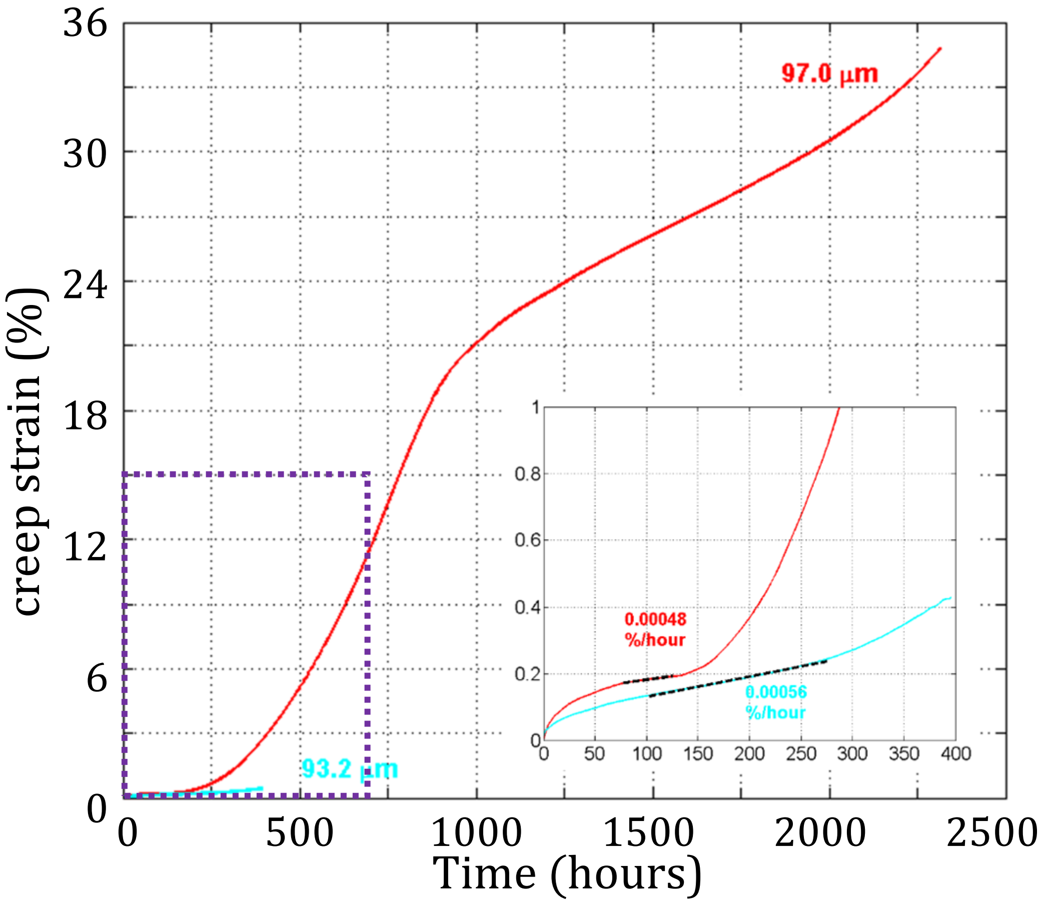
$$\dot{D}_c = \left[\frac{Y(\sigma^d)}{S_{c1}}\right]^{S_{c2}} \frac{1}{(1-D)^k}$$ (**Kachanov** law)

(J. Lematire, J. Eng. Mat. Technol., 1985;
L.M. Kachanov, The Theory of Creep, 1967)

Classic Chaboche law

1st attempts: 'simple' creep curve

800H creep in air at 980°C and 13.8 [MPa]



(B. Gardiner, PhD. thesis, 2014)

Identification of parameters

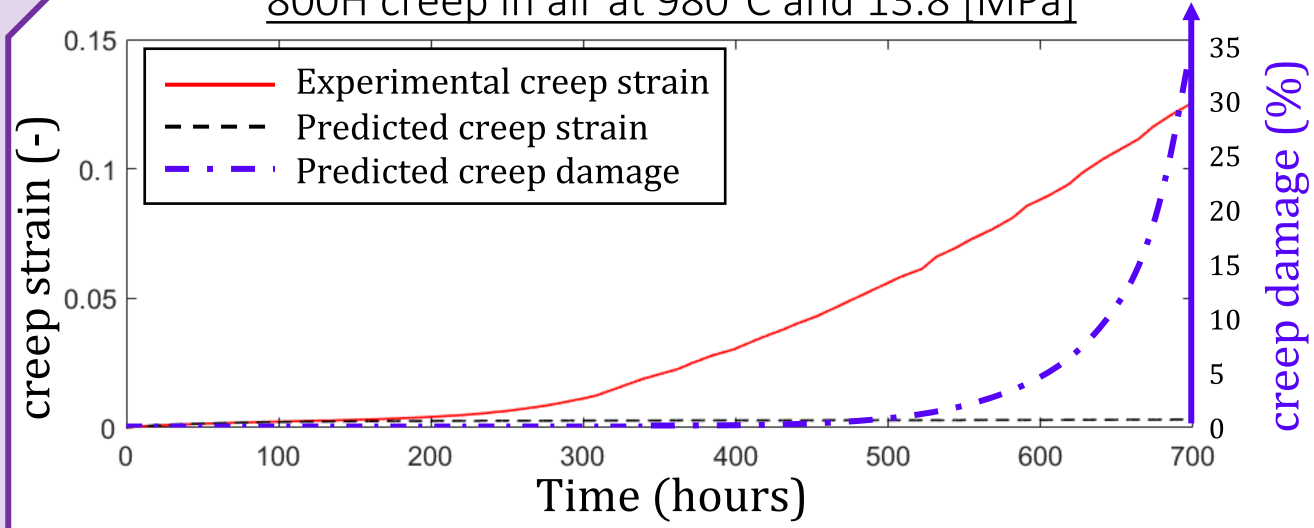
Elastic parameters → Direct (literature)

Backstress parameters
Norton law parameters
Damage parameters
→ Inverse (Levenberg-Marquardt algorithm)

(E. Betaieb et al., IJMF,2022)

First results with available law

800H creep in air at 980°C and 13.8 [MPa]



Modified viscoplastic law

Modifications

○ Viscoplastic law: **Graham-Walles (GW)** approach

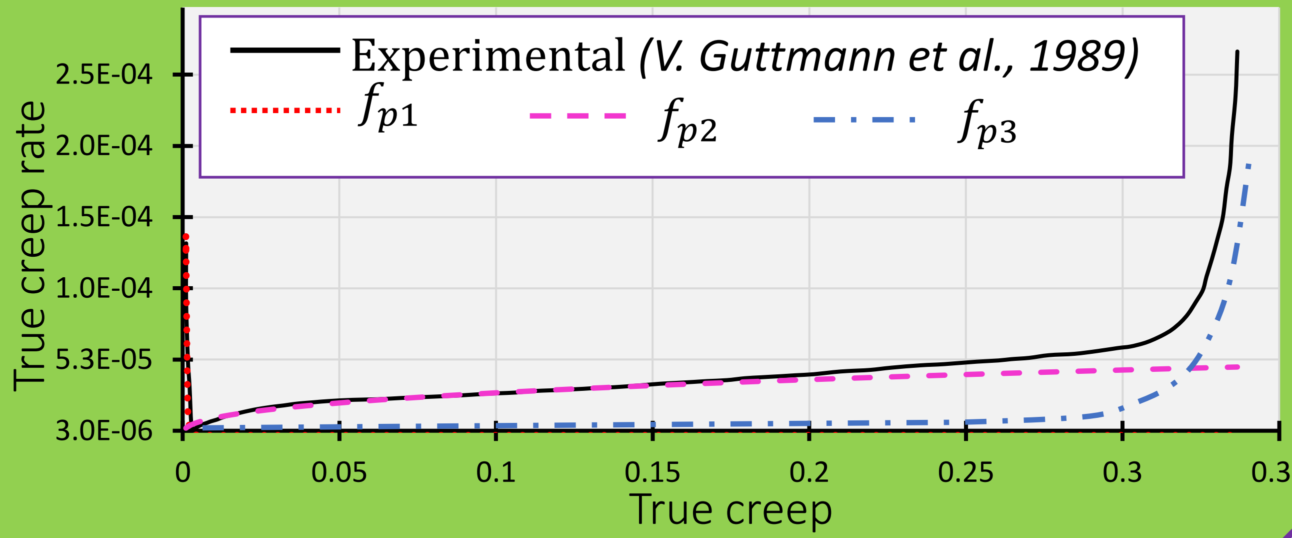
$$\dot{\bar{\epsilon}}^p = \sum_{j=1}^{vp_i} K_j e^{\frac{T}{C}} [\Sigma_{VM}^{eq}]^{n_j} (\bar{\epsilon}^p)^{m_j} + K_T \sigma |\dot{T}| (\bar{\epsilon}^p)^{m_T}$$

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

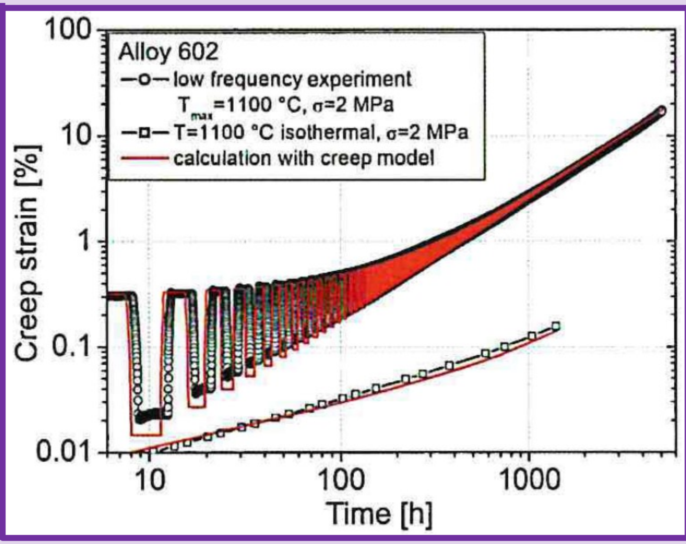
○ Damage law: **Darmstadt** formulation

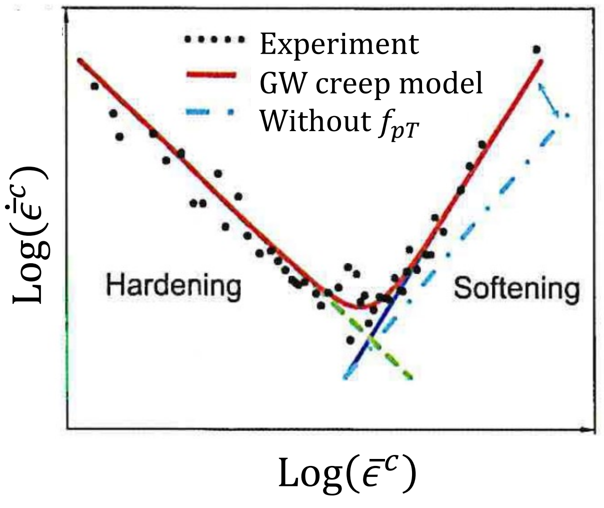
$$\dot{D} = K_D \Sigma_{VM}^{eq} + K_{TD} |\dot{T}| (\bar{\epsilon}^p)^{m_{TD}}$$

800H creep in air at 1000°C and 35 MPa



Previous works





(N. Kaushik Karthik, PhD thesis, 2020;
N. Kaushik Kathik et al., ECHT, 2019;
N. Schmitz et al., 111th AM of the G.A., 2019)

Algorithm flowchart

INPUT

- Miscellaneous material law parameters
- State variables: $\underline{\boldsymbol{\sigma}}_n, \underline{\mathbf{X}}_{i_n}, \bar{\epsilon}^p_n, D_n, \ldots$
- Strain, time and temperature: $\Delta\underline{\boldsymbol{\epsilon}}_{n+1}, \Delta t_{n+1}, \Delta \mathrm{T}_{n+1}$

↓

Update material parameters $f(T)$

↓

Elastic trial

Backstress tensor: $\underline{\mathbf{X}}_{i_{n+1}} = f\left(\underline{\mathbf{X}}_{i_{n+1}}, \ldots\right)\underline{\mathbf{X}}_{i_n}$

Trial stress: $\underline{\boldsymbol{\sigma}}^{TRIAL}_{n+1} = \underline{\boldsymbol{\sigma}}_n + \Delta\underline{\underline{\mathbf{C}}}^e \cdot \underline{\boldsymbol{\epsilon}}^e + \underline{\underline{\mathbf{C}}}^e \cdot \Delta\underline{\boldsymbol{\epsilon}}^e$

↓

$J_2(\underline{\boldsymbol{\sigma}} - \underline{\mathbf{X}}) - \sigma_y \leq 0$?

- YES → Update
- NO → Viscoplastic case

Viscoplastic case

$$\begin{Bmatrix} \Delta\underline{\boldsymbol{\epsilon}}^e \\ \Delta\bar{\epsilon}^p \\ \Delta\underline{\boldsymbol{\sigma}} \\ \Delta\underline{\mathbf{X}}_i \\ \Delta D \end{Bmatrix}_{n+1} \Longrightarrow \begin{aligned} \Delta\underline{\boldsymbol{\epsilon}}^e &= f(\Delta\bar{\epsilon}^p, \Delta\underline{\boldsymbol{\sigma}}, \Delta\underline{\mathbf{X}}_i, \Delta D) \\ \Delta\bar{\epsilon}^p &= f(\Delta\bar{\epsilon}^p, \Delta\underline{\boldsymbol{\sigma}}, \Delta\underline{\mathbf{X}}_i, \Delta D) \\ \Delta\underline{\boldsymbol{\sigma}} &= f(\Delta\underline{\boldsymbol{\epsilon}}^e, \Delta\underline{\boldsymbol{\sigma}}, \Delta D) \\ \Delta\underline{\mathbf{X}}_i &= f(\Delta\bar{\epsilon}^p, \Delta\underline{\boldsymbol{\sigma}}, \Delta\underline{\mathbf{X}}_i, \Delta D) \\ \Delta D &= f(\Delta\bar{\epsilon}^p, \Delta\underline{\boldsymbol{\sigma}}, \Delta\underline{\mathbf{X}}_i, \Delta D) \end{aligned}$$

↓

Application of Radial Return Mapping algorithm

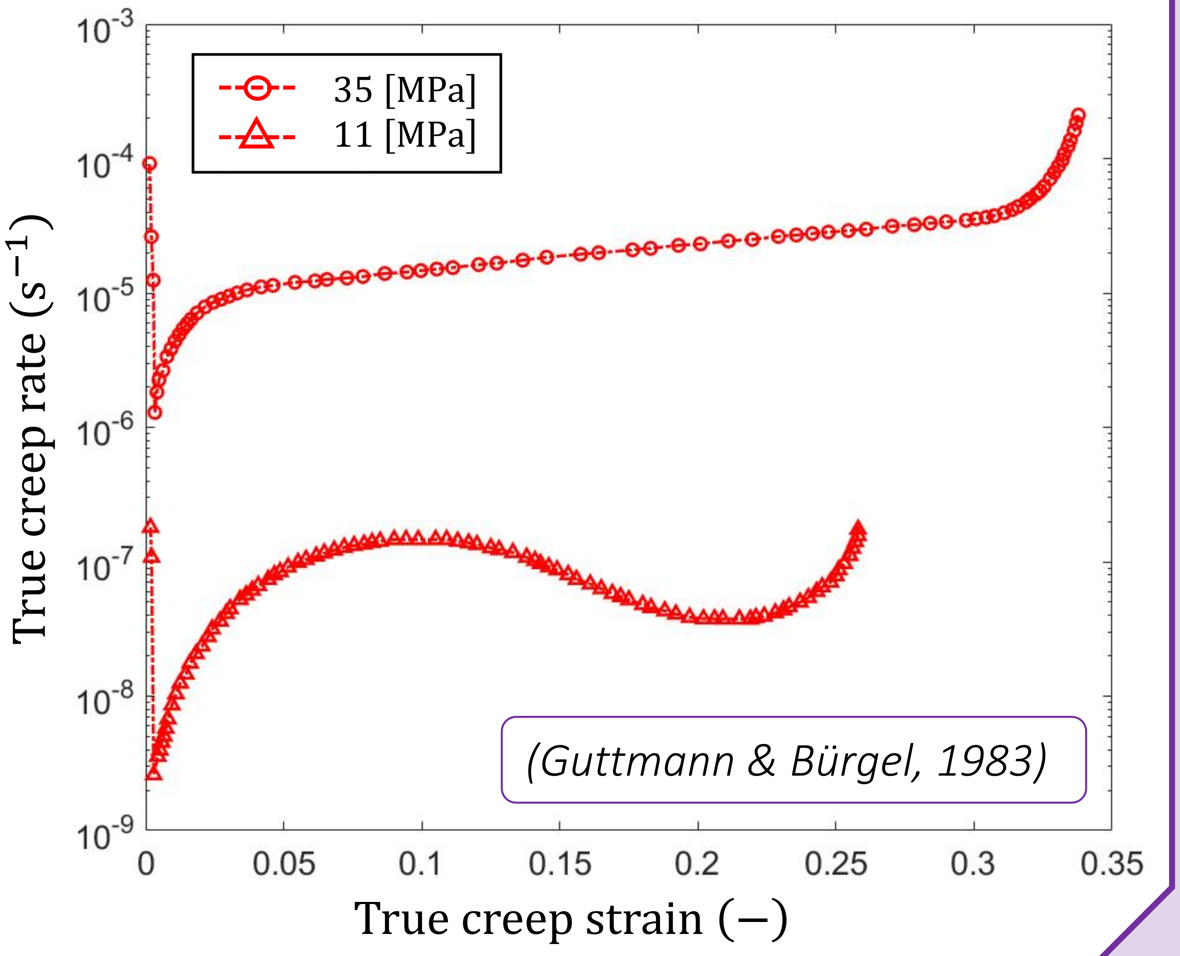
↓ Calculate

Update / **Calculate**: State variables for (*n+1*)

$\Delta\underline{\boldsymbol{\epsilon}}^e_{n+1}, \bar{\epsilon}^p_{n+1}, \underline{\boldsymbol{\sigma}}_{n+1}, \underline{\mathbf{X}}_{i_{n+1}}, \Delta D_{n+1}$

Application

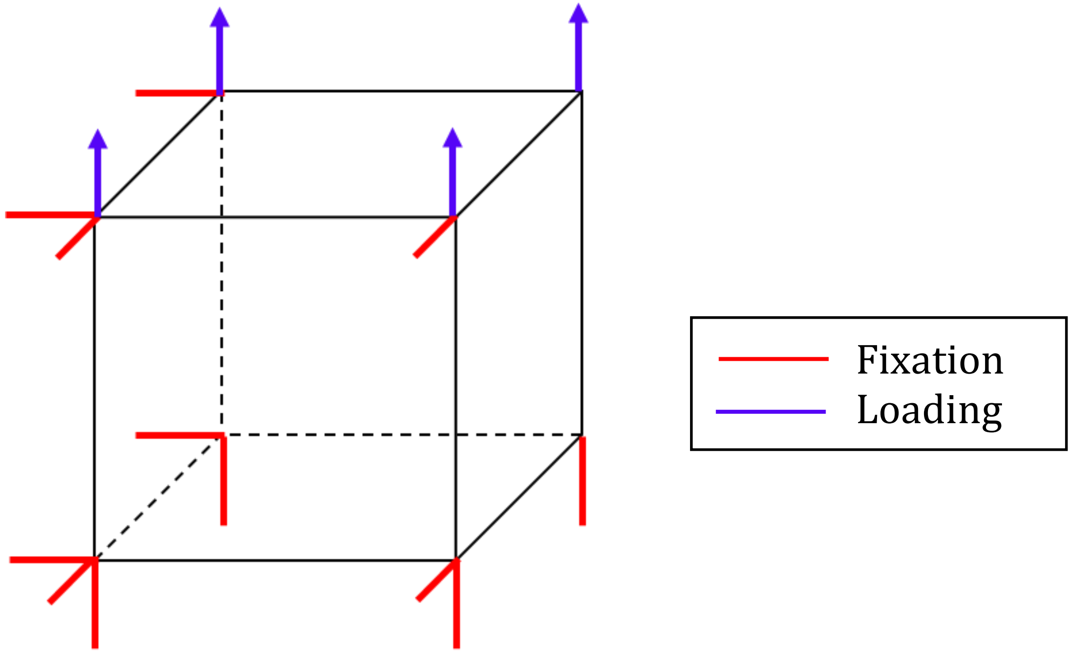
Experimental data



Simulation in FE software *Lagamine*

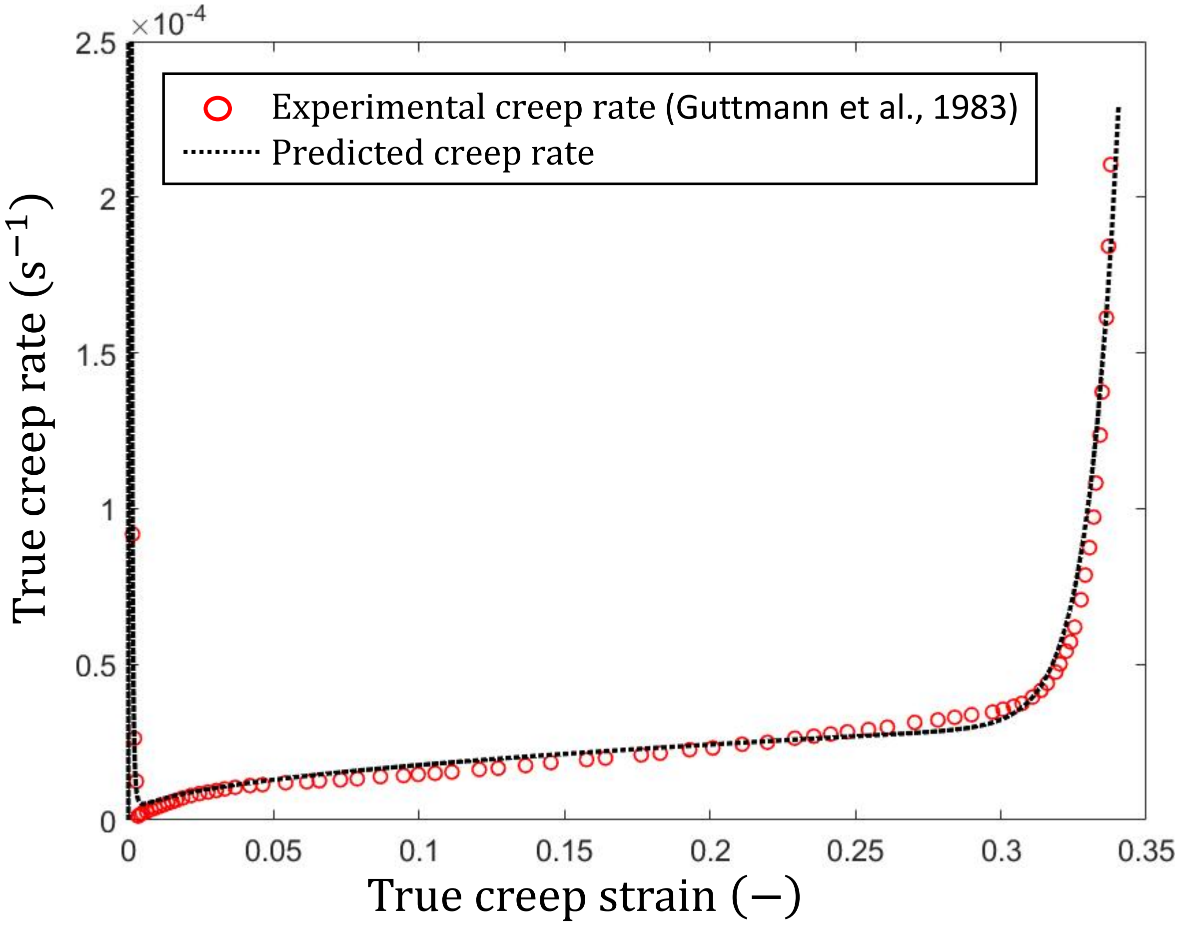
Single element: **BWD3T**

- Thermomechanical
- 8 nodes
- 4 DOF (*x*,*y*,*z*,T)
- 1 integration point



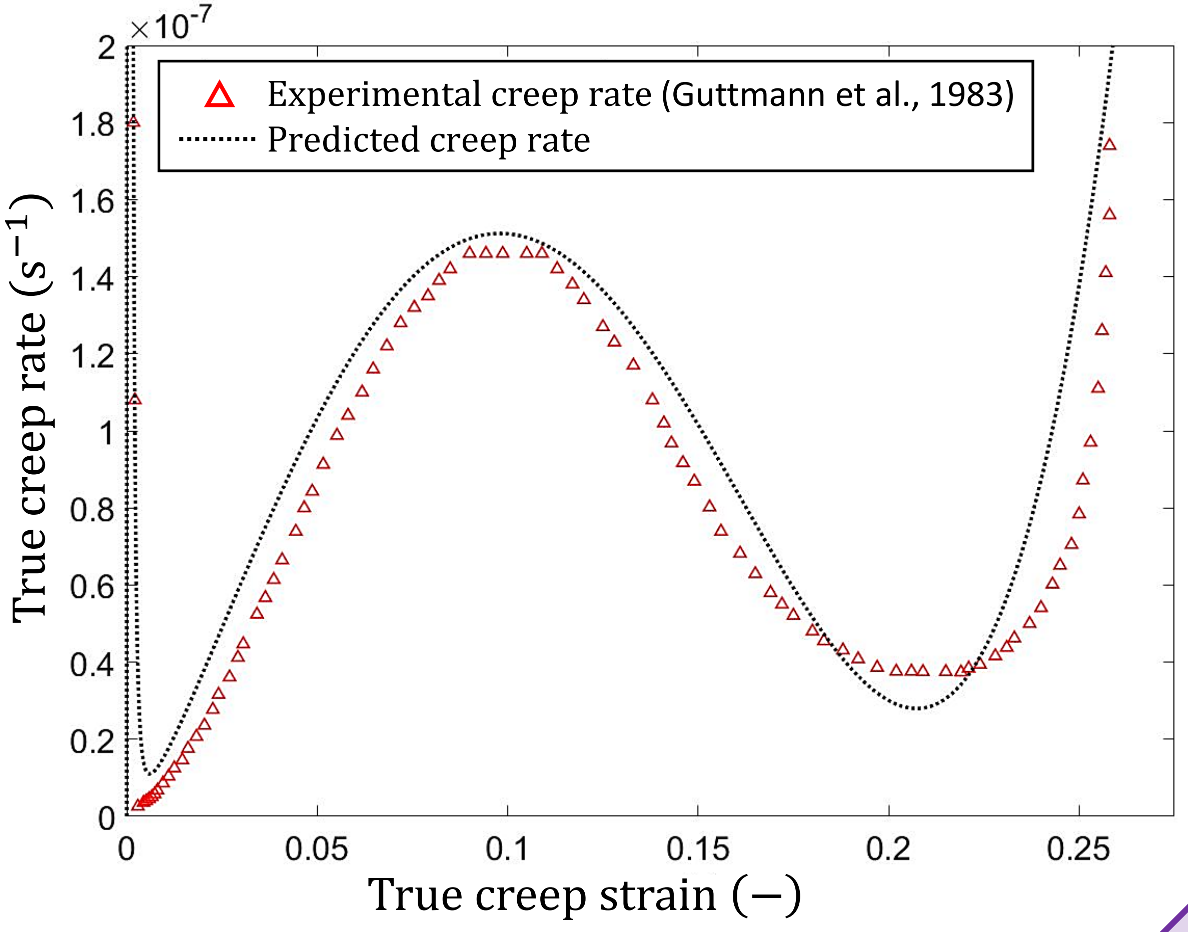
800H creep in air at 1000°C & 35 MPa

Experimental and predicted creep rate v/s creep



800H creep in air at 1000°C & 11 MPa

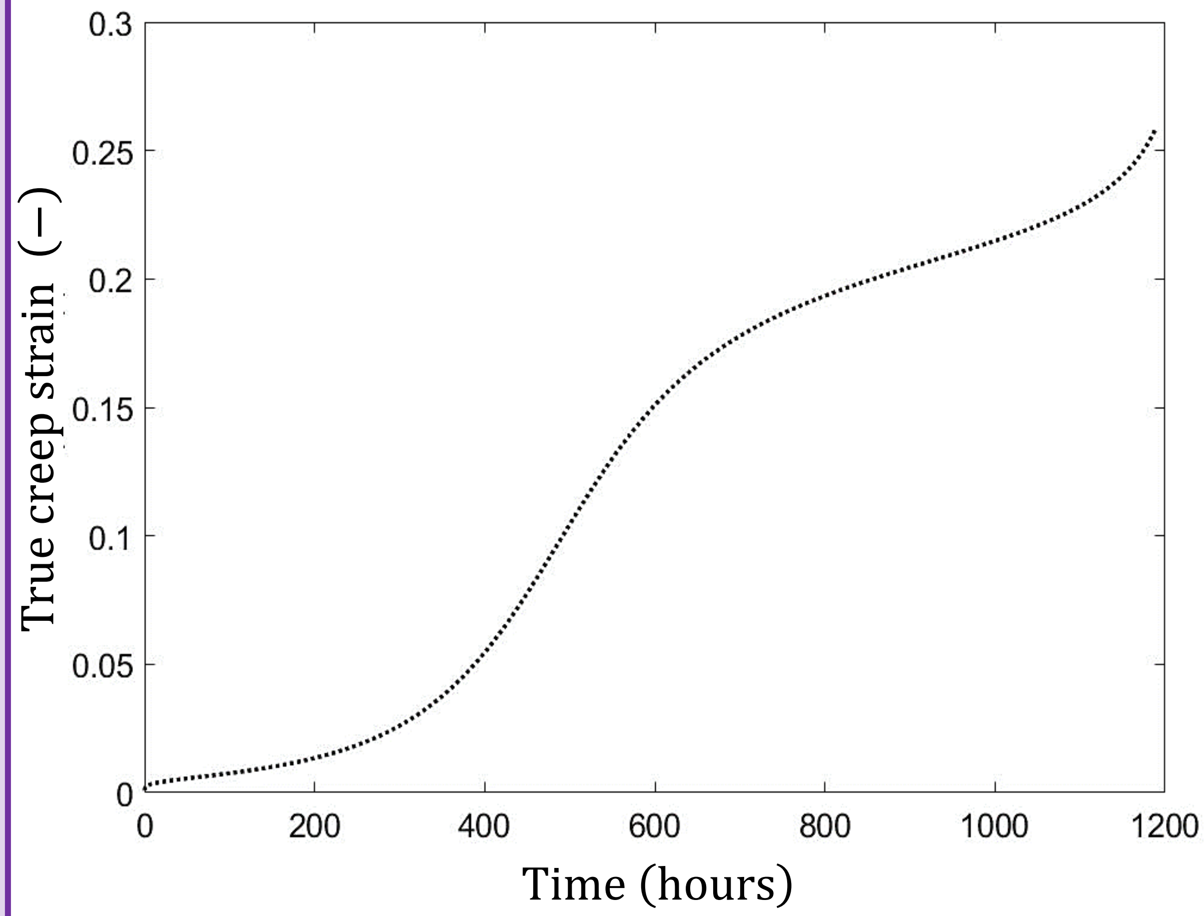
Experimental and predicted creep rate v/s creep



ACOMEN 2022

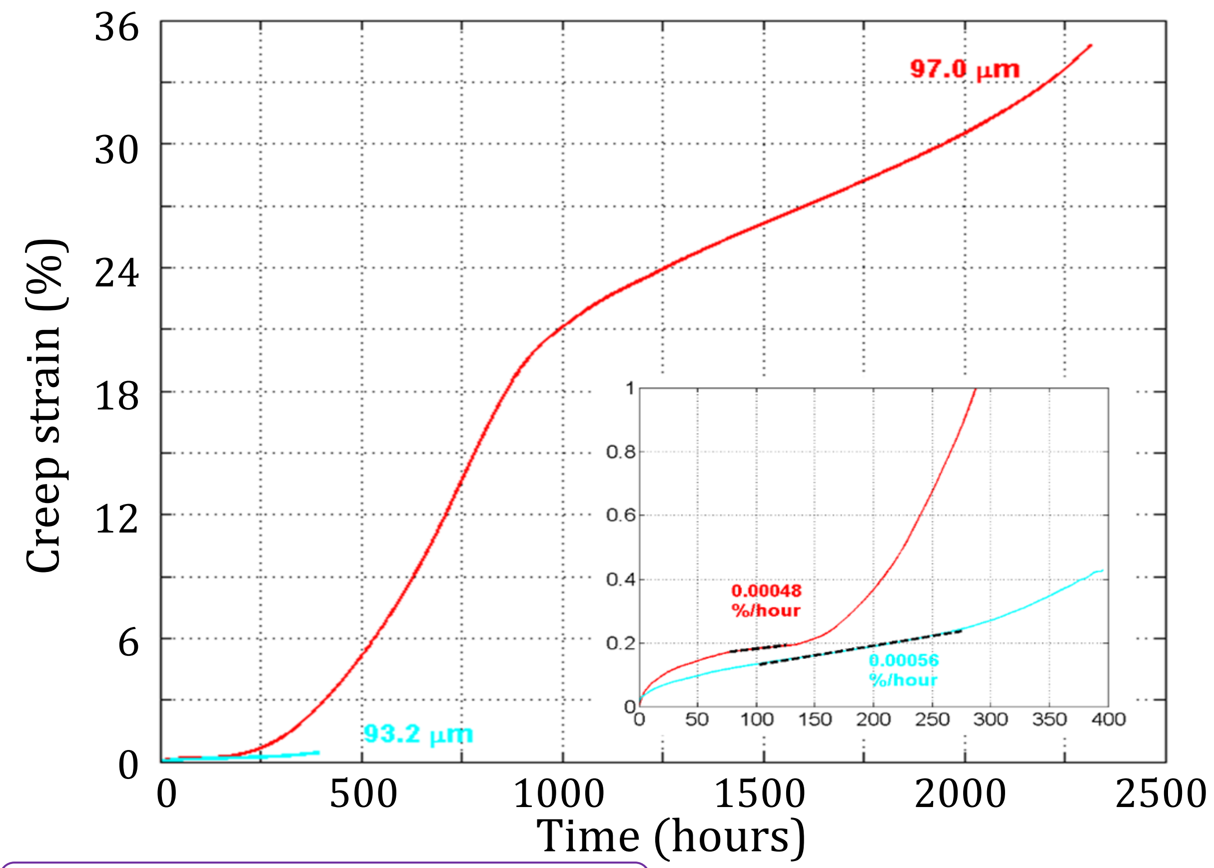
800H creep in air at 1000°C & 35 MPa

Predicted creep v/s time curves



800H creep in air at 980°C & 14 MPa

800H creep in air at 980°C and 13.8 [MPa]

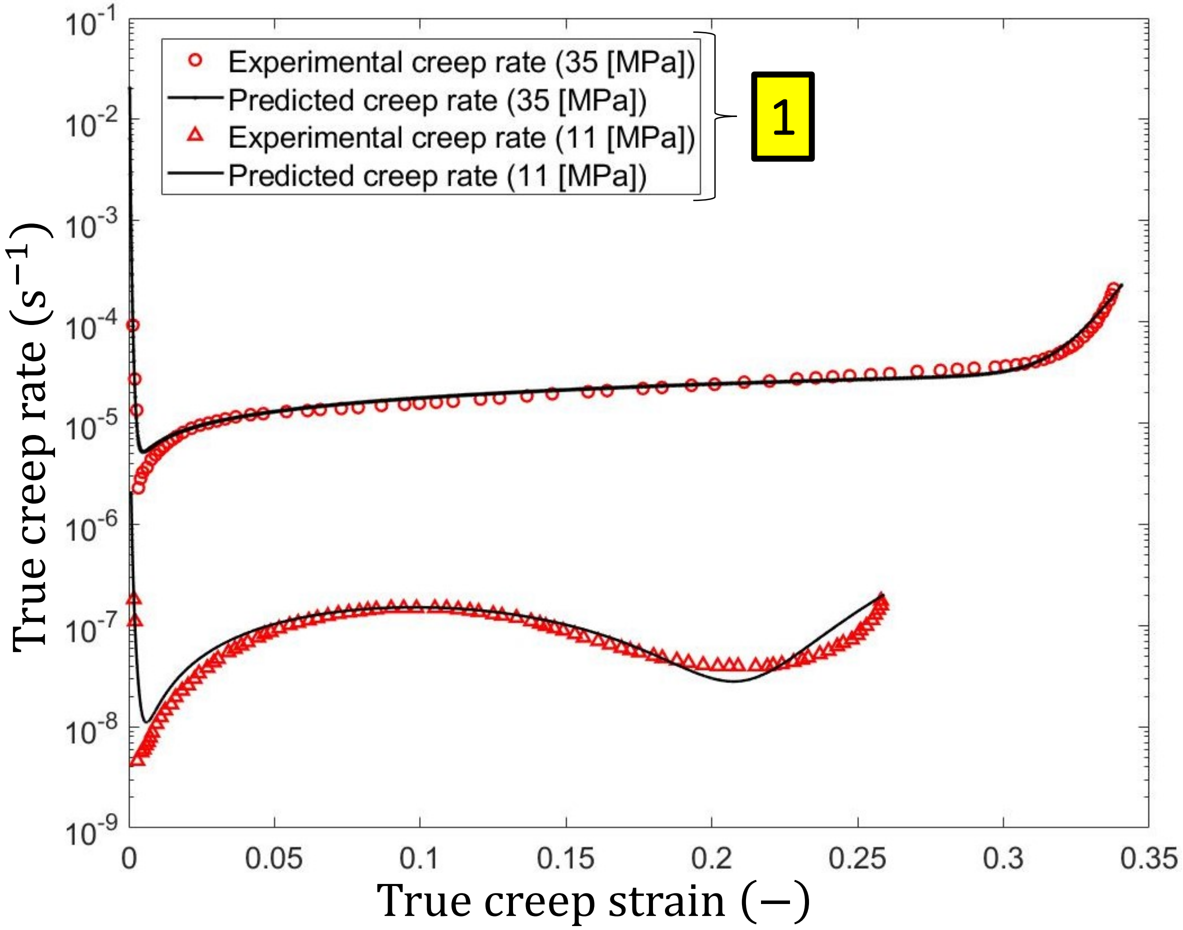


(B. Gardiner, PhD. thesis, 2014)

Conclusions & Remarks

Creep prediction

Creep rate v/s creep curves of 800H alloy at 1000°C



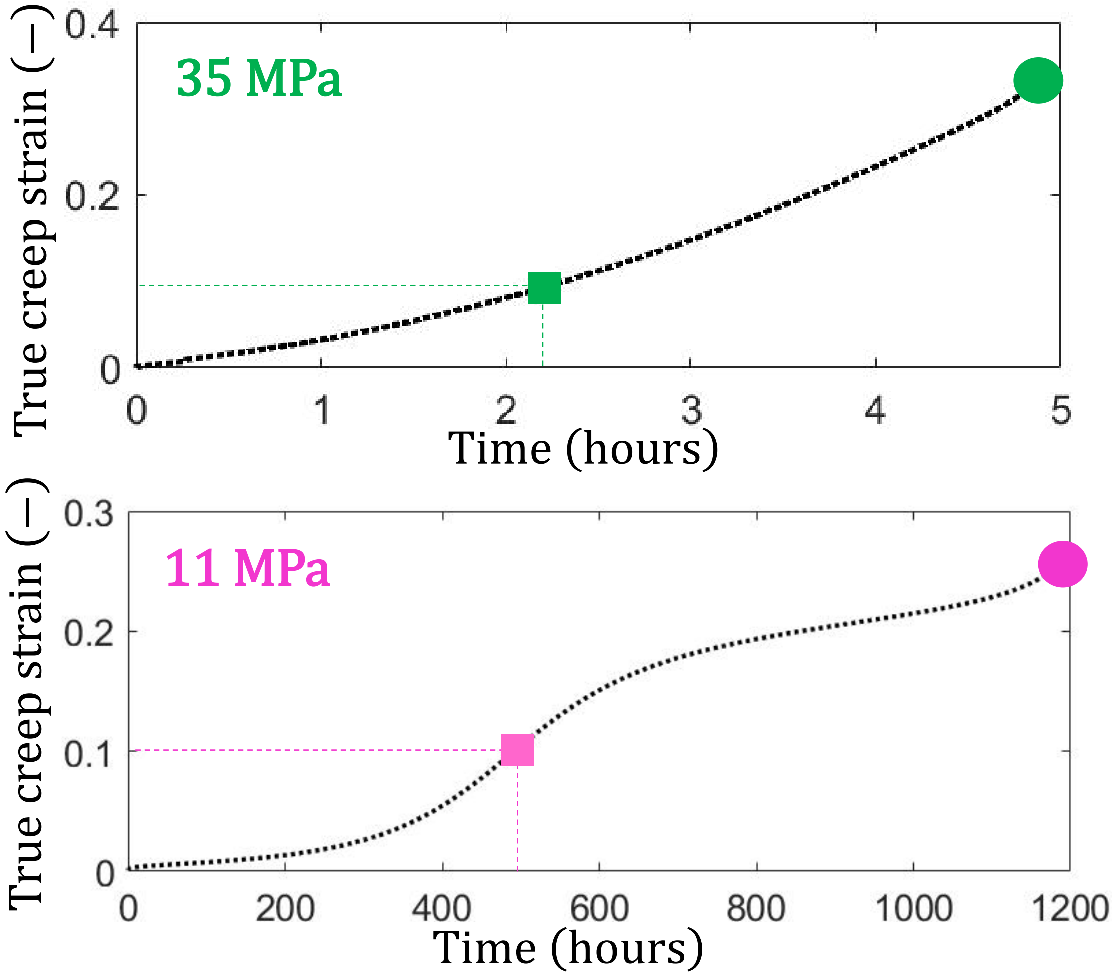
1

- Remarkable capabilities for predicting the complex creep behavior of 800H alloy

- Accuracy of the model must be assessed
  - Parameters identification
    - New reliable experimental data
    - New parameter identification approach
  - New nitridation-dedicated function
    - $\dot{\bar{\epsilon}}^p_N = K_N e^{\frac{T}{C}} \left[\Sigma^{eq}_{VM}\right]^{n_N} (\bar{\epsilon}^p)^{m_N} \rightarrow f\begin{pmatrix}\text{Stress}\\ \text{Temperature}\\ \text{Geometry}\\ \text{Creep strain}\end{pmatrix}$

Time-to-rupture prediction

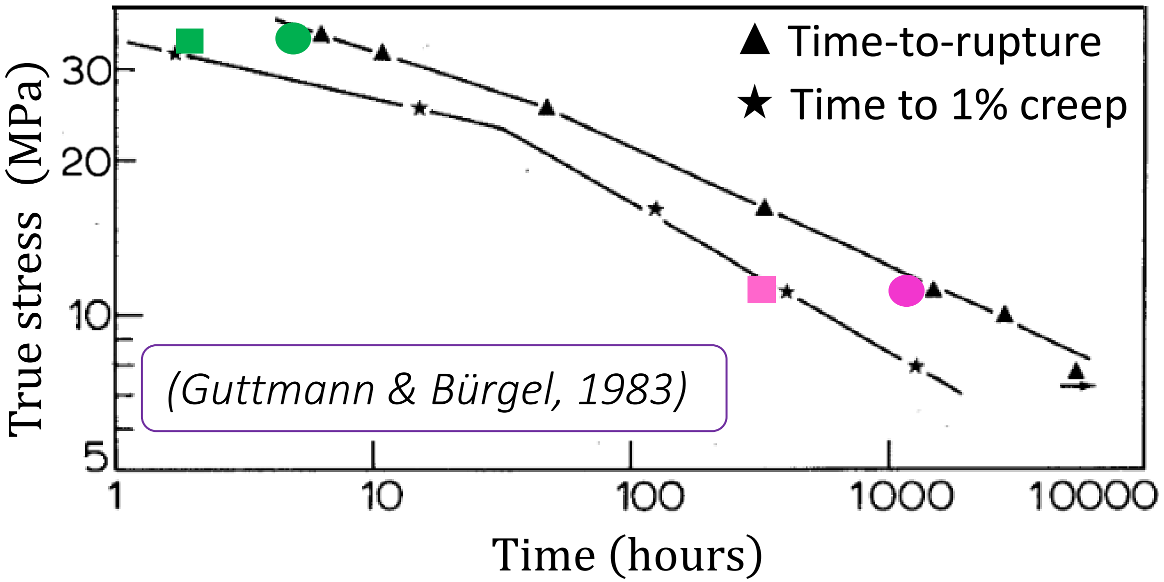
Creep strain v/s time curves of 800H alloy at 1000°C



2

► Results are found within experimental limits

Creep rupture strength and stress for 1% creep strain



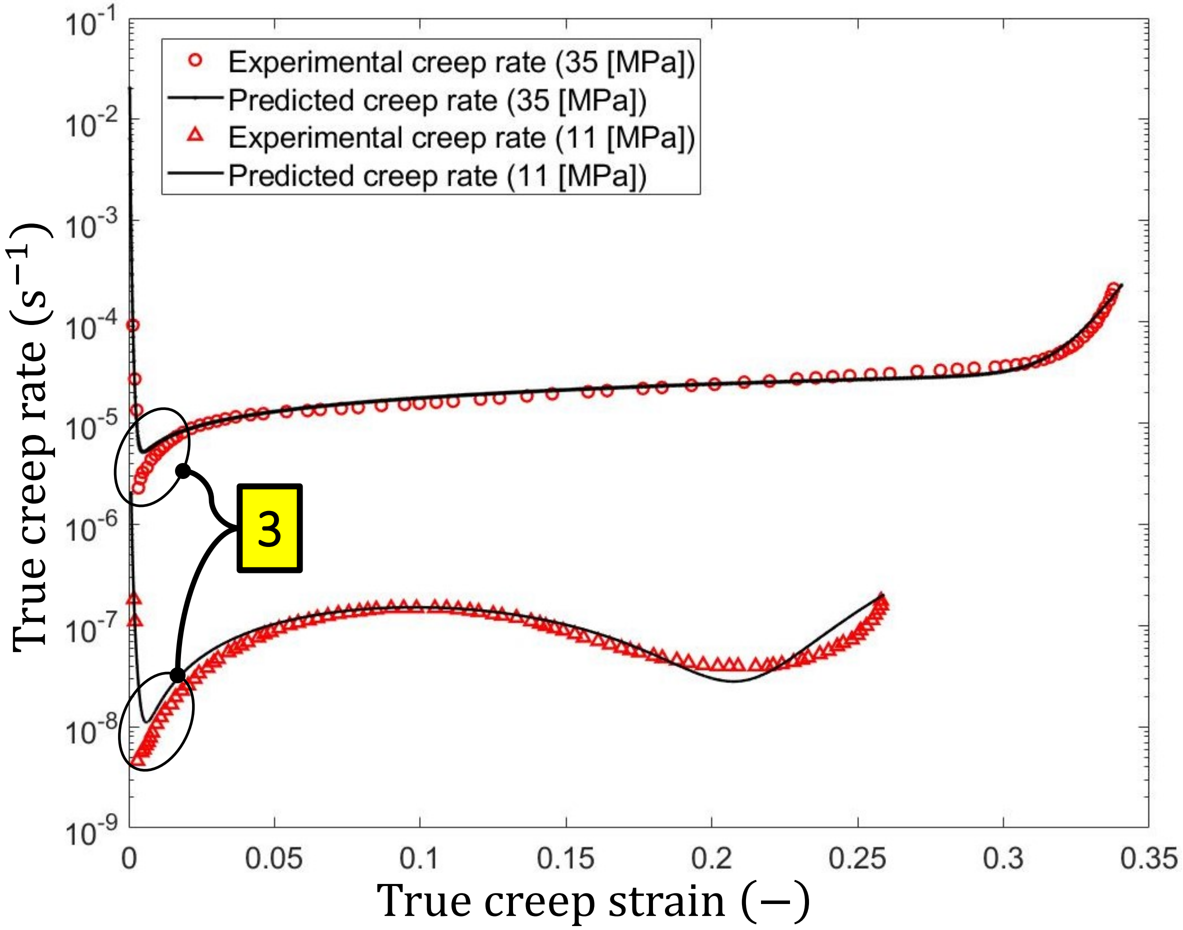
► Damage model still to be assessed

- Constant thermal loadings
- Thermomechanical fatigue

Conclusions & Remarks

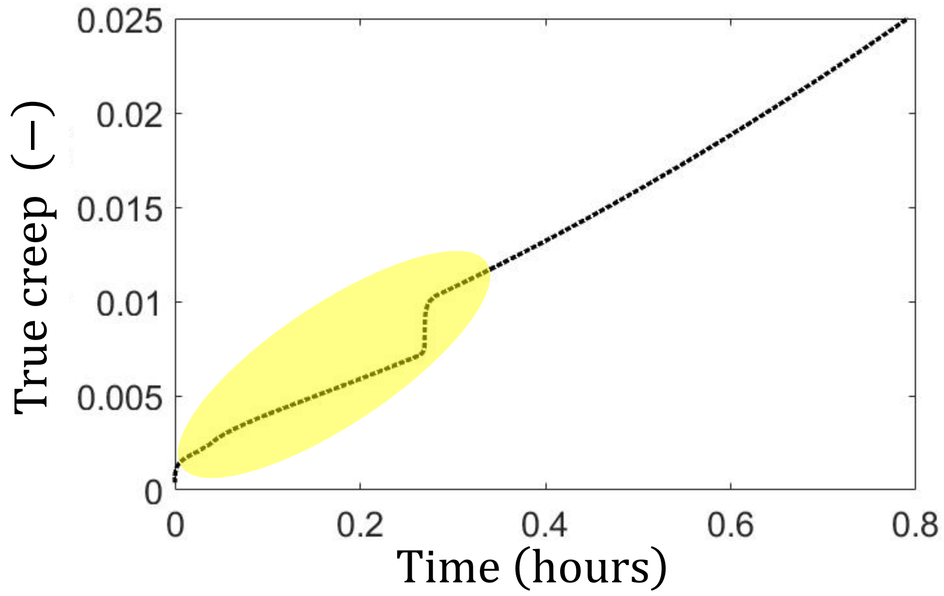
Numerical aspect

Creep rate v/s creep curves of 800H alloy at 1000°C



3

- **The model exhibits good numerical convergence**
  - Comparable to Chaboche-type law
- **Convergence issues within creep rate slope changes**
  - Visualization in creep v/s time curves:



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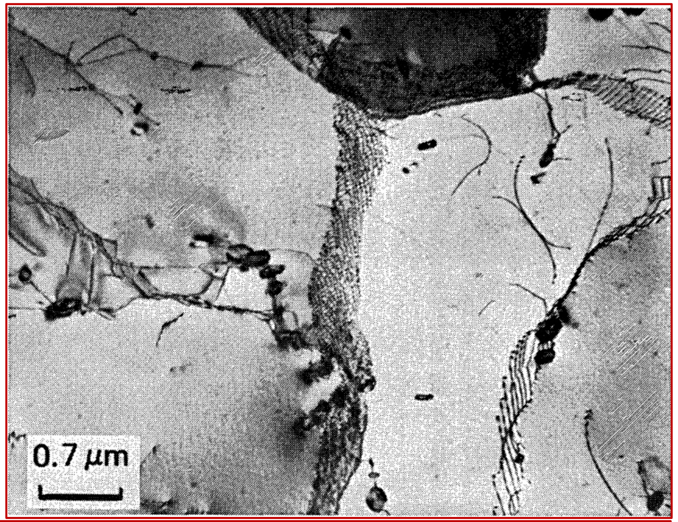
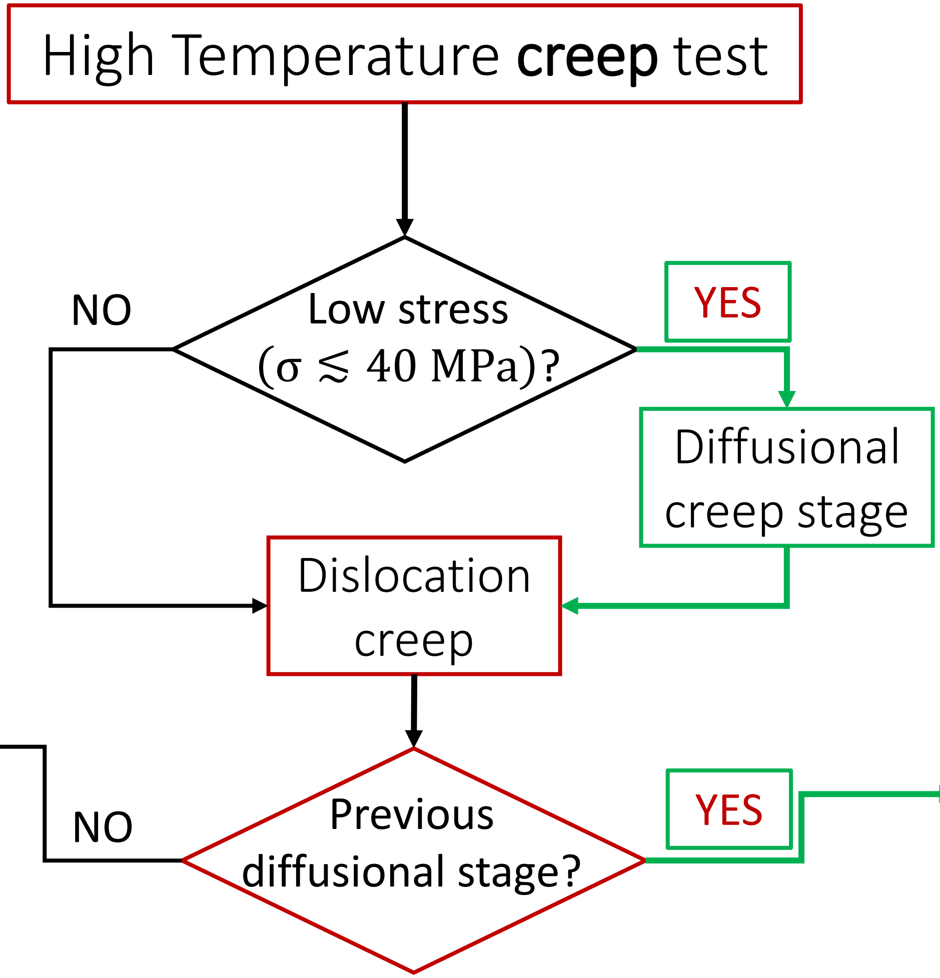
Detailed 800H creep micromechanics

(Guttmann & Bürgel, 1983)

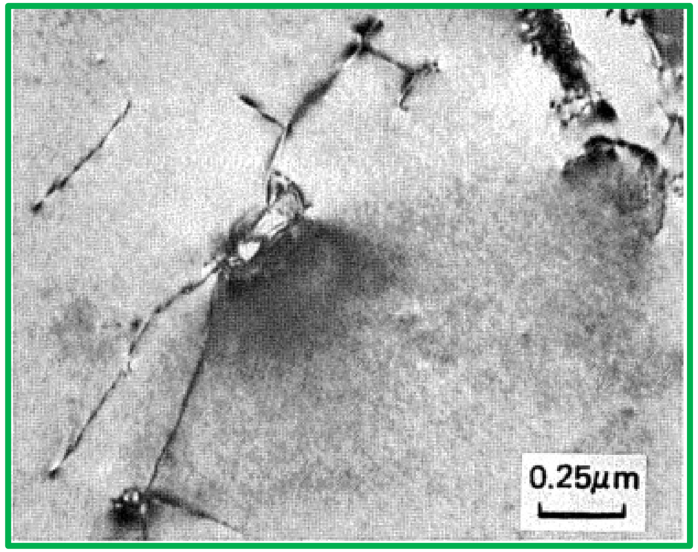


Testing temperature: 900°C
Testing stress: 35 [MPa]
Time: 170 h

Dissolved atoms act as pinning points for dislocations, forming sub-grains



(Guttmann & Bürgel, 1983)



Testing temperature: 1000°C
Testing stress: 5 [MPa]
Time: 1900 h

Dislocations are free to move towards grain boundaries.

Annex 2: Integration scheme

$$\underline{R} = \begin{cases} \underline{R}_{\boldsymbol{\epsilon}^e} = \\ \underline{R}_{\bar{\epsilon}^p} = \\ \underline{R}_{\boldsymbol{\sigma}} = \\ \underline{R}_{\mathbf{X}_j} = \\ \underline{R}_D = \end{cases}$$

	Reference integration scheme	New integration scheme
$\underline{R}_{\boldsymbol{\epsilon}^e} =$	$\Delta\underline{\boldsymbol{\epsilon}}_{n+1} - \Delta\underline{\boldsymbol{\epsilon}}^{th}_{n+1} - \Delta\underline{\boldsymbol{\epsilon}}^{p}_{n+1} - \Delta\underline{\boldsymbol{\epsilon}}^{e}_{n+1}$	$\Delta\underline{\boldsymbol{\epsilon}}_{n+1} - \Delta\underline{\boldsymbol{\epsilon}}^{th}_{n+1} - \Delta\underline{\boldsymbol{\epsilon}}^{p}_{n+1} - \Delta\underline{\boldsymbol{\epsilon}}^{e}_{n+1}$
$\underline{R}_{\bar{\epsilon}^p} =$	$\Sigma^{eq}_{VM} - \sigma_0 - Q[1-\exp(-b\bar{\epsilon}^p)] - K(\dot{\bar{\epsilon}}^p)^{\frac{1}{N}}$	$\Delta\bar{\epsilon}^p{}_{n+1} - \sum_{j=1}^{vp_i} K_j e^{\frac{\mathrm{T}}{C}}[\Sigma^{eq}_{VM}]^{n_j}(\bar{\epsilon}^p_{n+1})^{m_j}\Delta t - K_T \ldots$
$\underline{R}_{\boldsymbol{\sigma}} =$	$\Delta\underline{\boldsymbol{\epsilon}}^{e}_{n+1} - inv(\underline{\underline{\mathbf{C}}}^e_{n+1}) \cdot \underline{\tilde{\boldsymbol{\sigma}}}_{n+1}$	$\Delta\underline{\boldsymbol{\epsilon}}^{e}_{n+1} - inv(\underline{\underline{\mathbf{C}}}^e_{n+1}) \cdot \underline{\tilde{\boldsymbol{\sigma}}}_{n+1}$
$\underline{R}_{\mathbf{X}_j} =$	$\Delta\underline{\mathbf{X}}_{i\,n+1} - \frac{2}{3}C_j\Delta\underline{\boldsymbol{\epsilon}}_{n+1} - \cdots + \frac{1}{C_j}\frac{dC_j}{d\mathrm{T}}\Delta\mathrm{T}\underline{\mathbf{X}}_{i\,n+1}$	$\Delta\underline{\mathbf{X}}_{i\,n+1} - \frac{2}{3}C_j\Delta\underline{\boldsymbol{\epsilon}}_{n+1} - \cdots + \frac{1}{C_j}\frac{dC_j}{d\mathrm{T}}\Delta\mathrm{T}\underline{\mathbf{X}}_{i\,n+1}$
$\underline{R}_D =$	$\Delta D_{n+1} - \Delta D_f(\underline{\boldsymbol{\sigma}}_{n+1}, \bar{\epsilon}^p_{n+1}) + \Delta D_c(\underline{\boldsymbol{\sigma}}_{n+1}, D_{n+1})$	$D_{n+1} - K_D\Sigma^{eq}_{VM}\Delta t - K_{TD}\lvert\Delta\mathrm{T}\rvert(\bar{\epsilon}^p_{n+1})^{m_{TD}}$

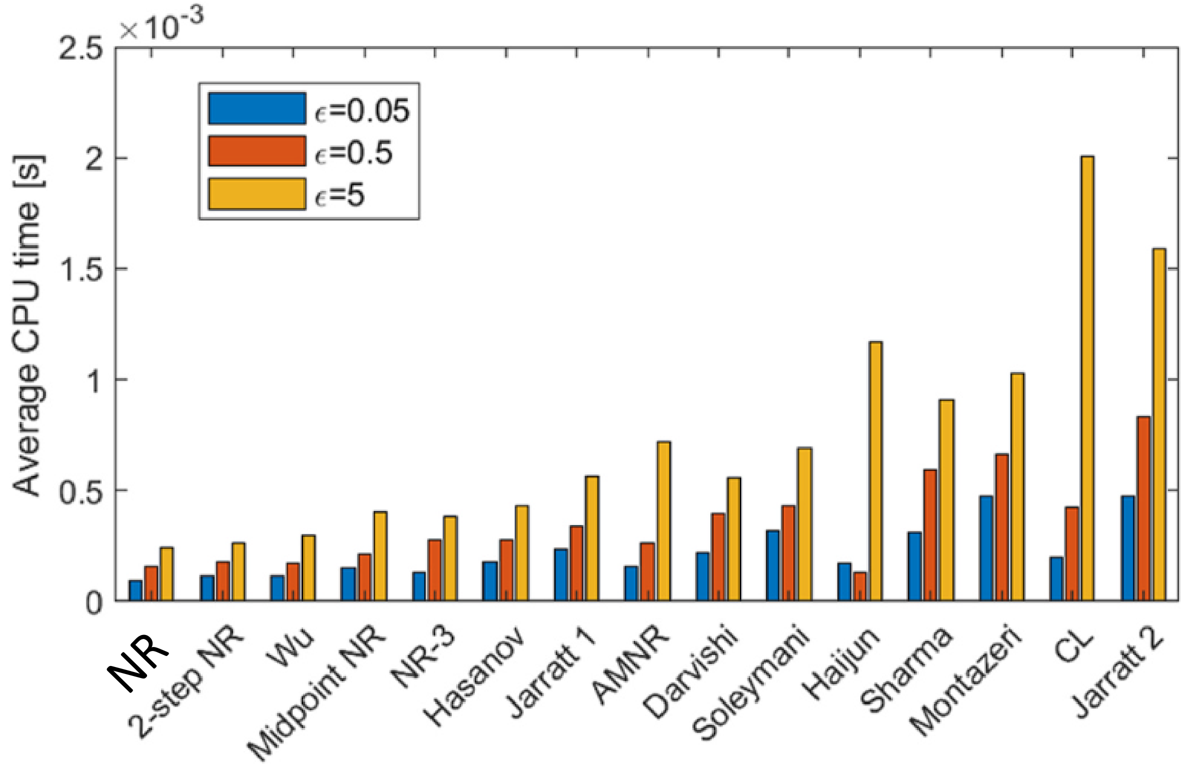
$\underline{R}$ Is our matrix of local residuals

Objective: $|\underline{R}| \approx 0$

Annex 3: Algorithm

Computational efficiency

Average CPU time for different resolution methods
applied for solving different equation systems



(H. Morch et al., FE in A&D, 2022)

Integration algorithm: NR

1-Dimension NR formula

$$x^{k+1} = x^k - \frac{R\left(x^k\right)}{R'\left(x^k\right)}$$

Our viscoplastic system

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

Calculation of $(\mathcal{J}\{\underline{R}\})^{-1}$

$$(\mathcal{J}\{\underline{R}\})^{-1} \cdot \underline{R} = \underline{A} \quad \Longrightarrow \quad \underline{R} = \underline{A} \cdot \mathcal{J}\{\underline{R}\}$$