Creep mechanisms of Incoloy 800H at high temperature

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

July 3rd, 2023

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Project funded by FRIA grant 4000-8987

Outlines

Research context
Industry & Science on 800H alloy

Creep macromechanics
- □ 800H creep macromechanics
- □ Finite element modelling

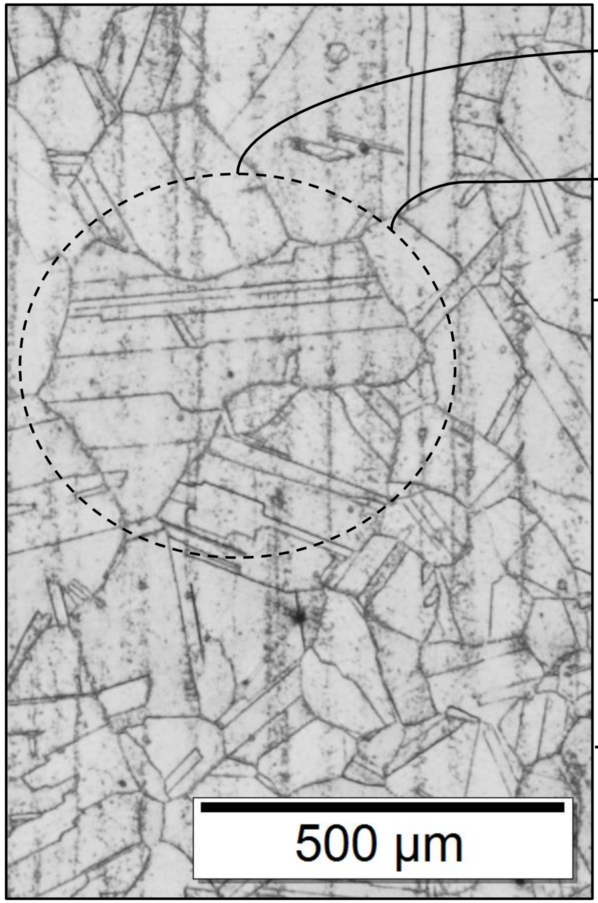
Creep micromechanics
- □ 800H creep micromechanics
- □ Experimental findings

Concluding remarks
- □ Multiscale correlation
- □ Research prospects

Industry & Science on 800H alloy

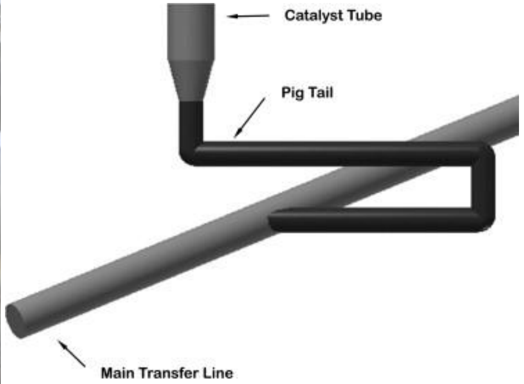
Incoloy 800H: a Fe-Ni-Cr austenitic alloy

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



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

- Used in many applications:
  - Petrochemical
  - Metallurgy
  - Heat exchangers
  - Power generation
  - …



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

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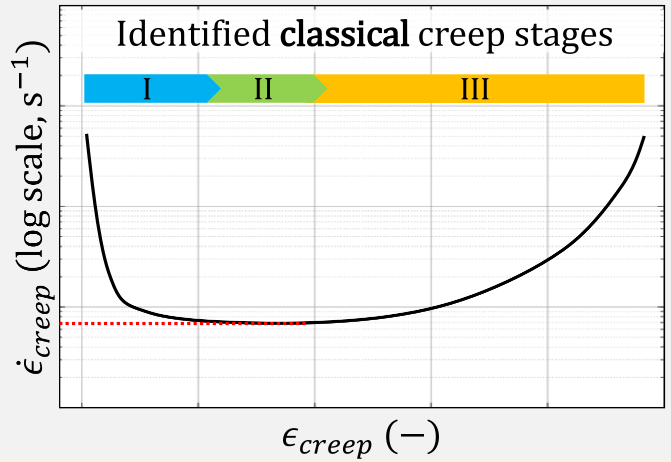
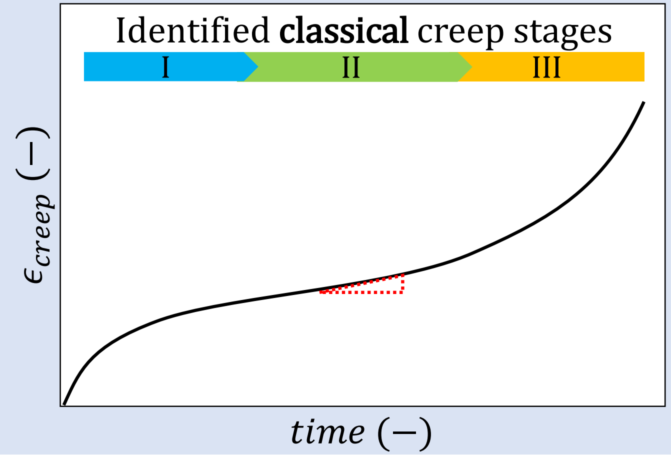
Creep test

High-mid **stress** & Low-mid **T**
σ ≳ 40 [MPa] | T° ≲ 760°C

Creep strain rate v/s Creep strain

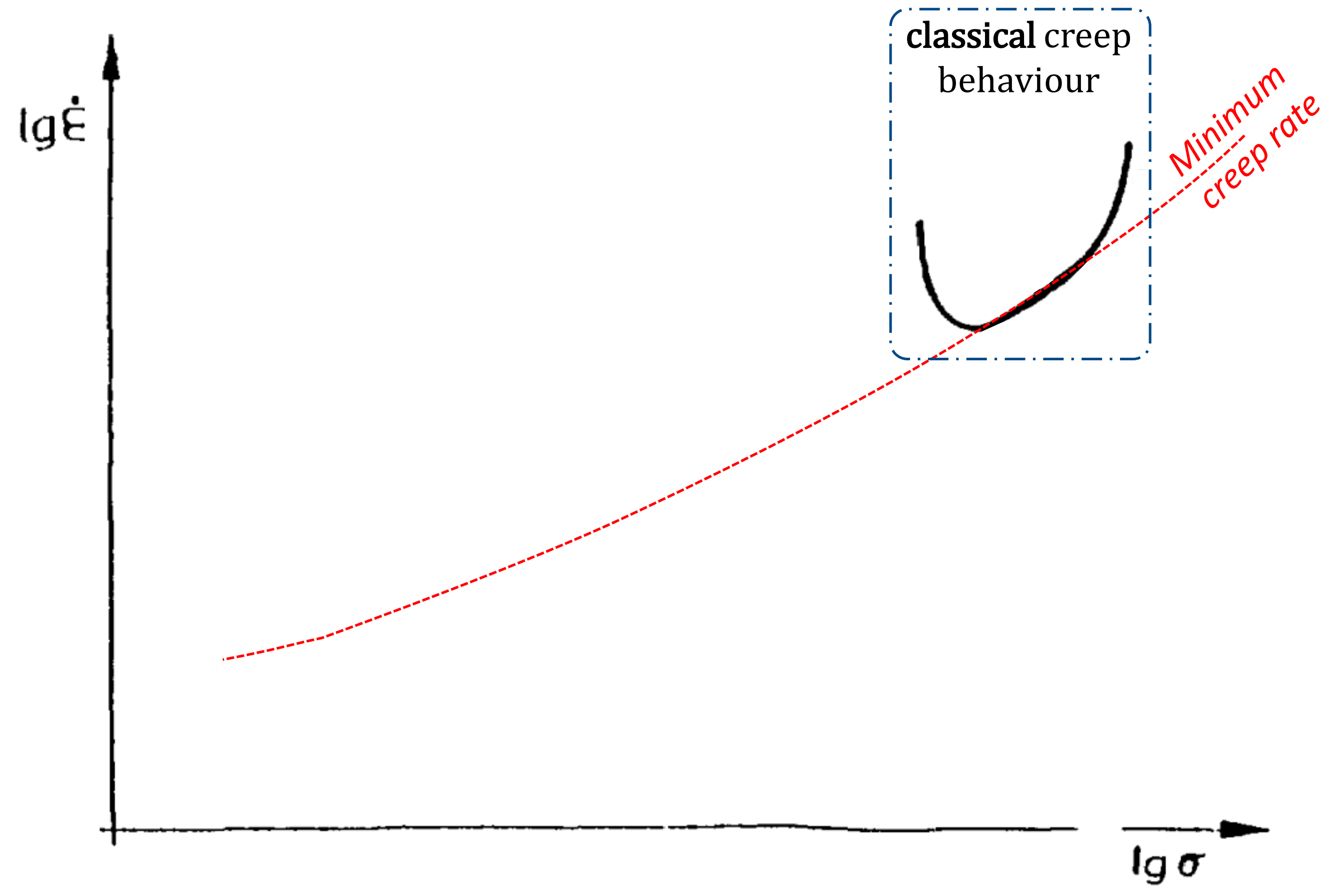


Creep strain v/s time



Classical creep behaviour

Qualitative creep rate – stress relation at 800°C



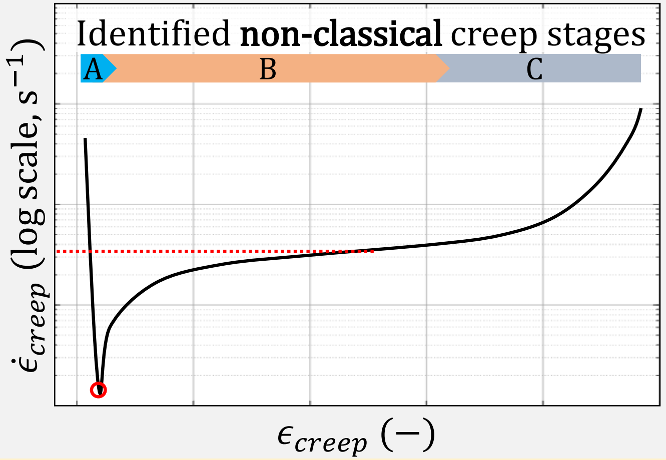
after H.P. Degischer et al., *High Temperature Alloys*, 1987

Creep test

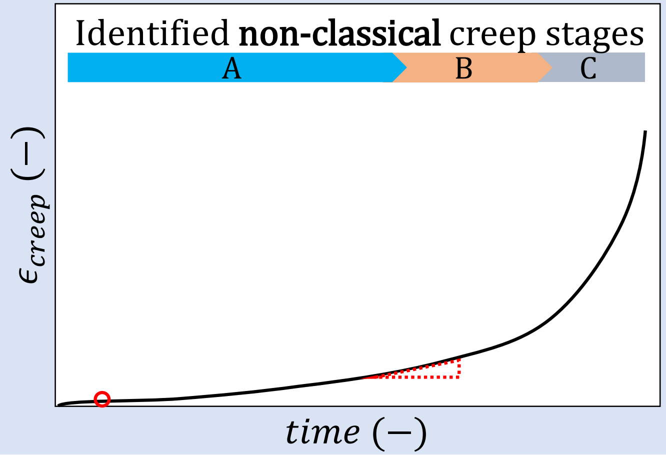
Low **stress** & high **T°**

Short creep test | inert gas test

Creep strain rate v/s Creep strain

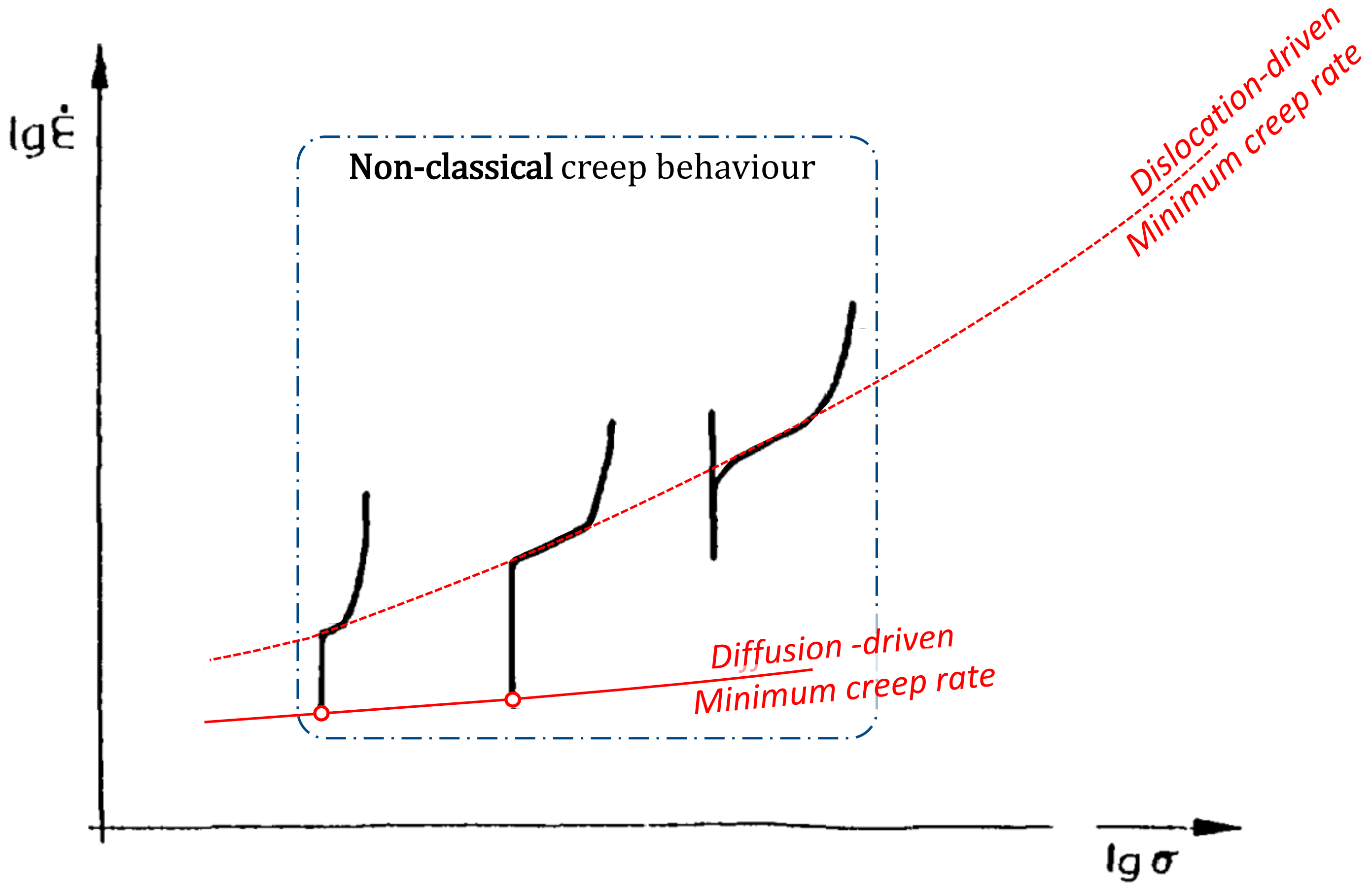


Creep strain v/s time



Non-classical creep behaviour: creep mechanism transition

Qualitative creep rate – stress relation at 800°C



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

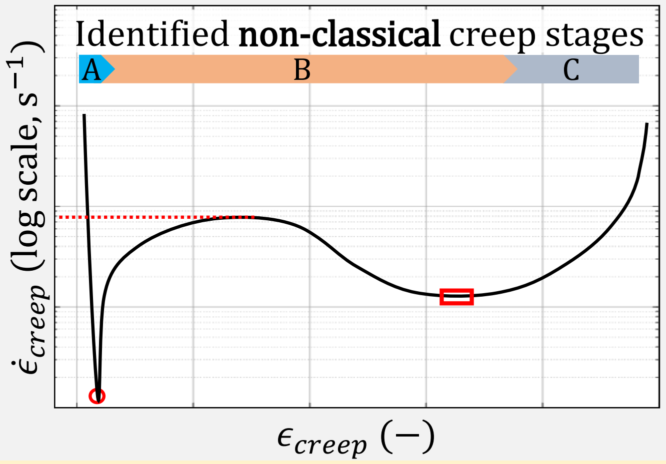
800H creep macromechanics

Creep test

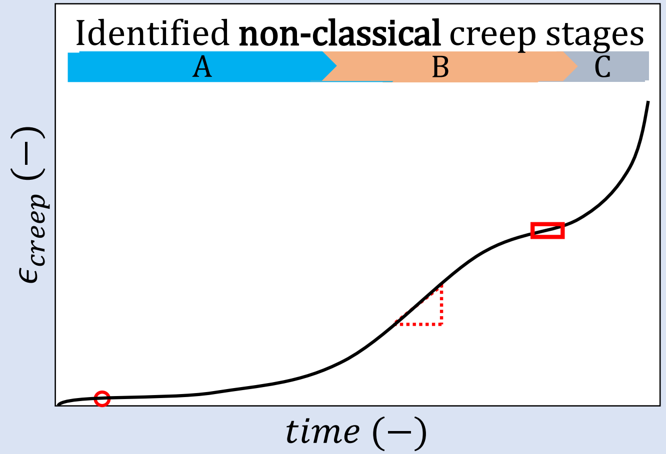
Low **stress** & high **T°**

Long creep test | non-inert gas test

Creep strain rate v/s Creep strain

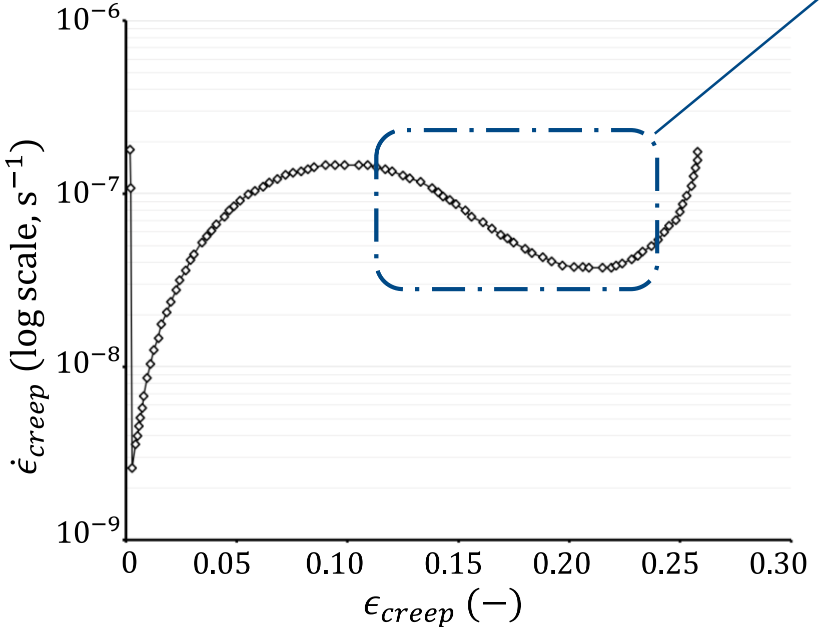


Creep strain v/s time



Non-classical creep behaviour: Two-step minima

Creep on 800H at 11 [MPa] & 1000°C



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

- **Why?**

1. Nitridation-induced creep hardening

Observed in 800H
V. Guttmann & R. Bürgel, 1983;
H.P. Degischer's team (GmbH, Austria)

2. Intergranular $M_{23}C_6$ carbides precipitation

Observed in similar Ni-austenitic alloys
T. Hatakeyama et al., 2021; 2022

Finite element modelling

Constitutive law: Chaboche-type law + Graham-Walles viscoplastic & damage function approach

Yield function: von-Mises criterion

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

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

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

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

Viscoplastic function 1: Norton power law

Damage function 1: Lemaitre + Kachanov

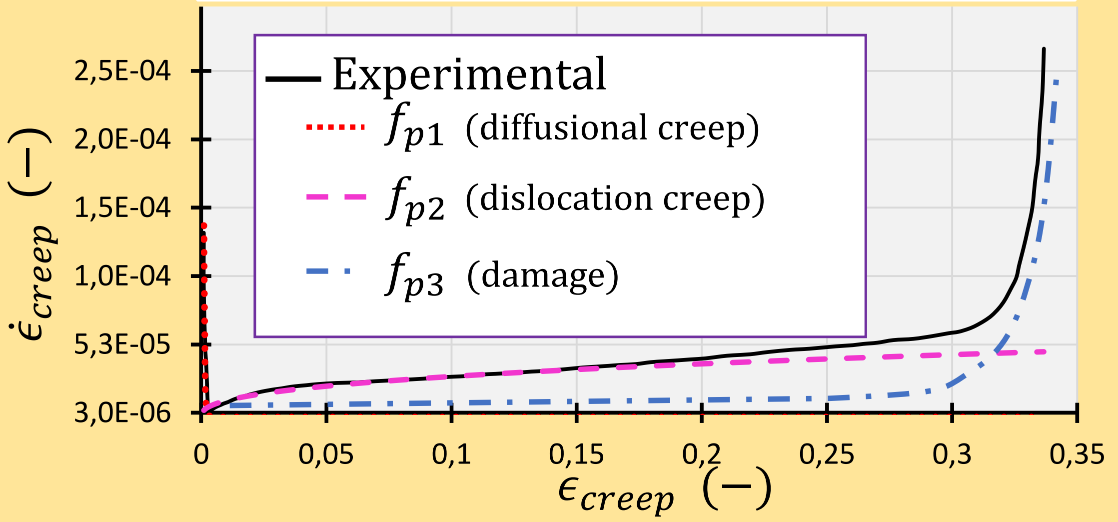
User Choice

Viscoplastic function 2: Graham-Walles approach [*]

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

1 Function <—> 1 phenomenon

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



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

Damage function 2: Graham-Walles approach [*]

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

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

$$\dot{D}_f = K_{TD}\left|\dot{T}\right|(\bar{\epsilon}^p)^{m_{TD}}$$

*: Model developed in IfW Darmstadt. See *Narayana K. Karthik, PhD Thesis, Aachen University, 2020*

Finite element modelling

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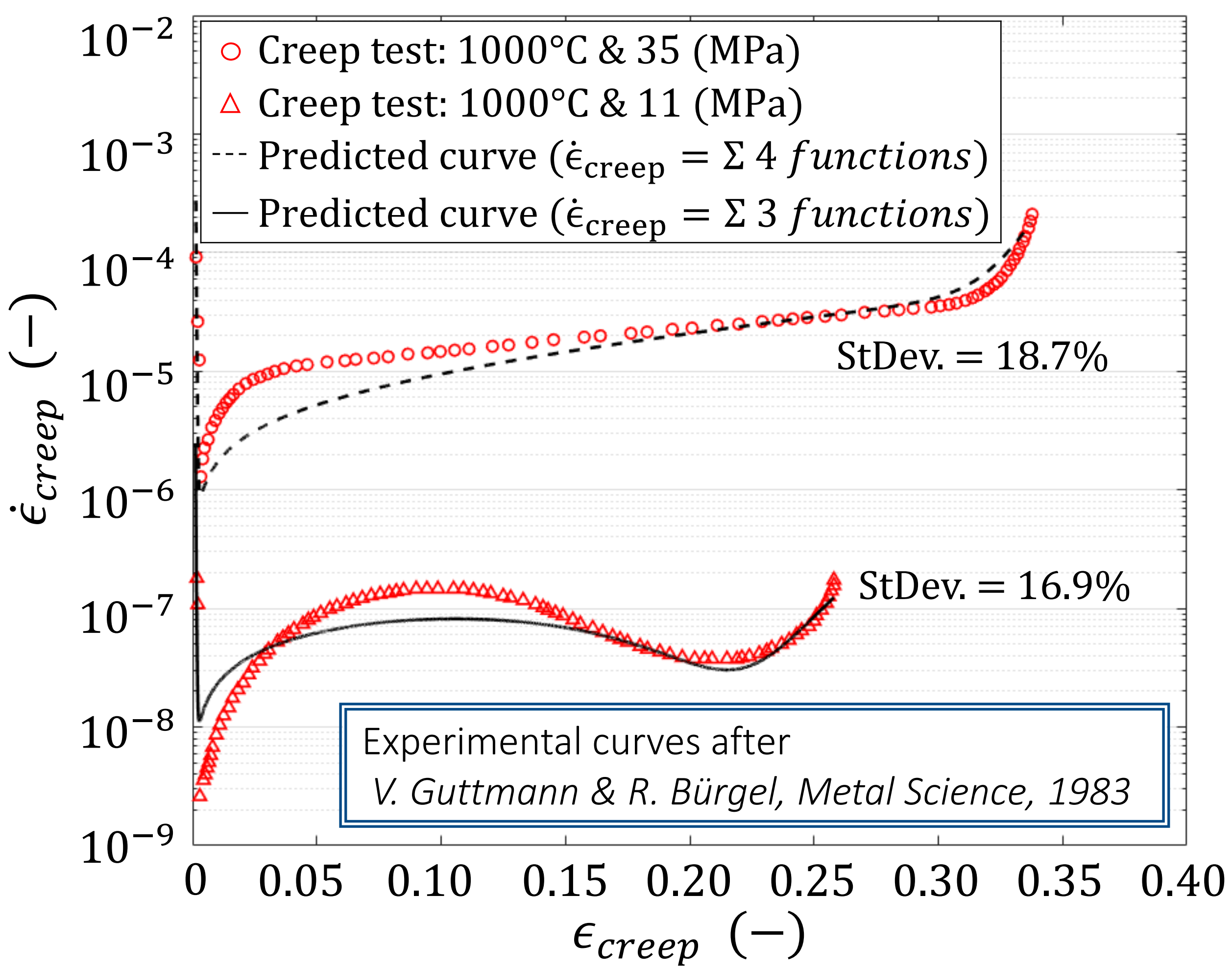
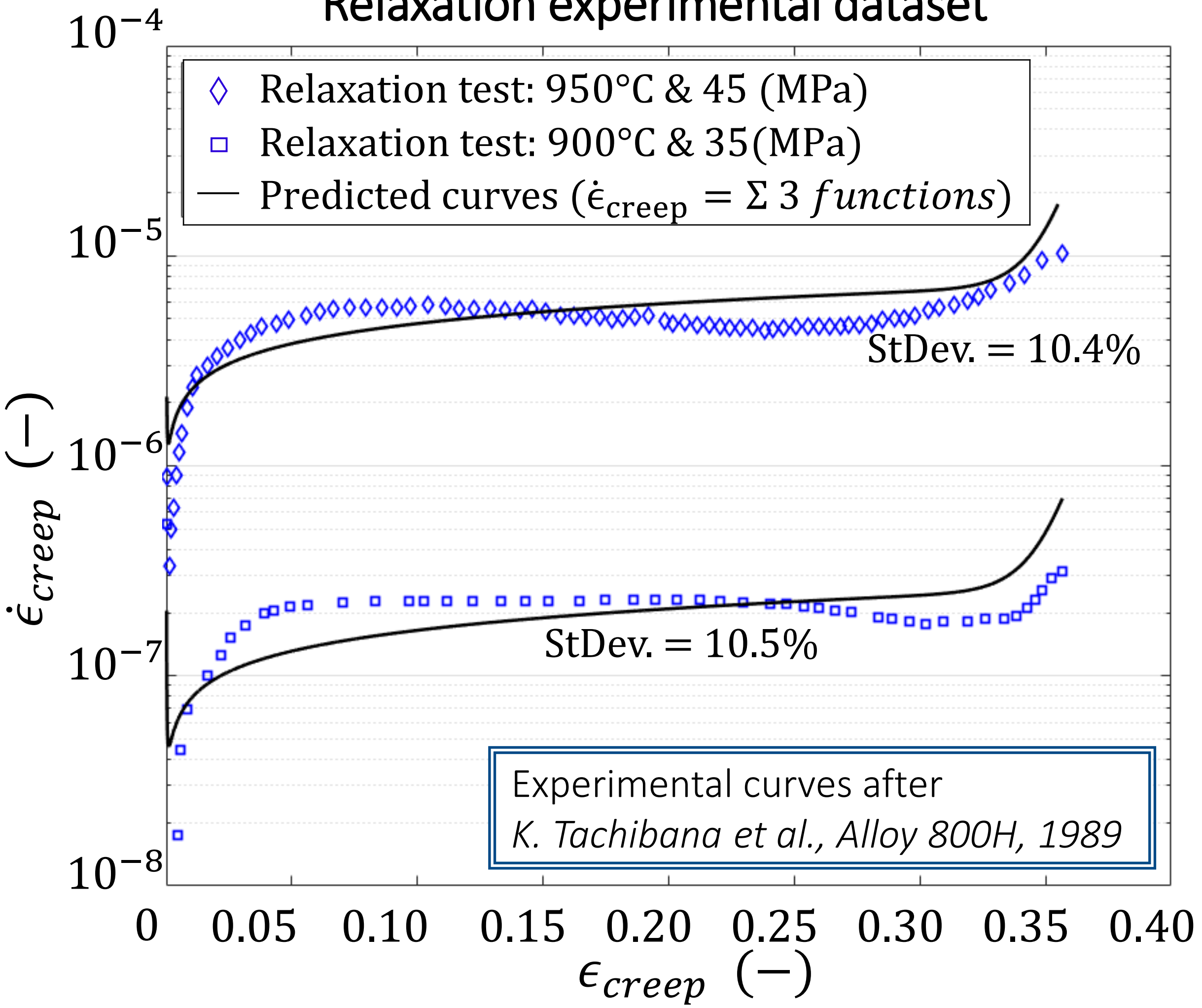
Constitutive law: Chaboche-type law + Graham-Walles viscoplastic & damage function approach

Creep experimental dataset



Experimental curves after
V. Guttmann & R. Bürgel, Metal Science, 1983

Relaxation experimental dataset



Experimental curves after
K. Tachibana et al., Alloy 800H, 1989

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Creep in 800H: a multiscale phenomenon

Smooth bar samples were placed in a furnace, where thermal and environmental conditions were simulated

Smooth bar 800H samples

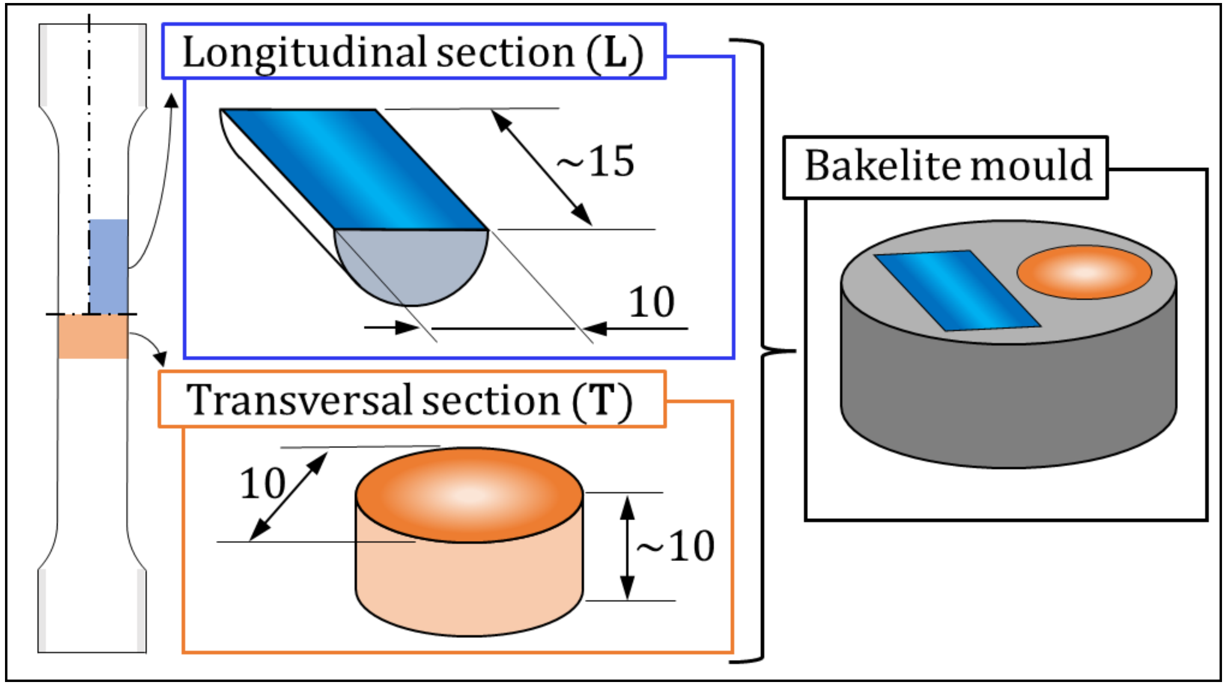
Geometries
- D05 5 [mm] diameter
- D10 10 [mm] diameter

Industrial furnace

Exposed to realistic environmental and thermal loadings

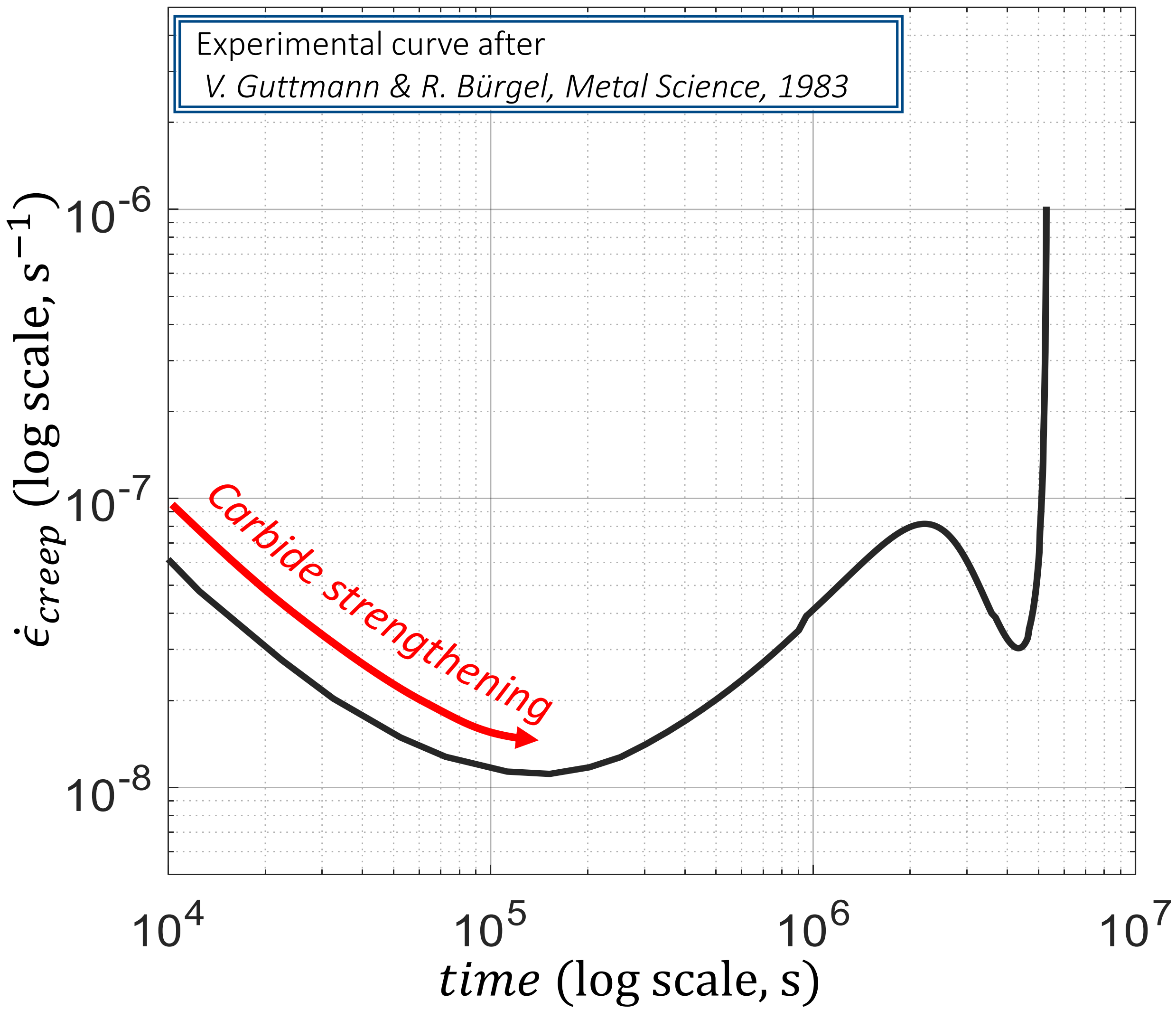
Tag	Description
N0	Sound material
N1	1 year in furnace
N2	2 years in furnace
N3	3 years in furnace
N4	4 years in furnace

1 D10 sample from each N-batch

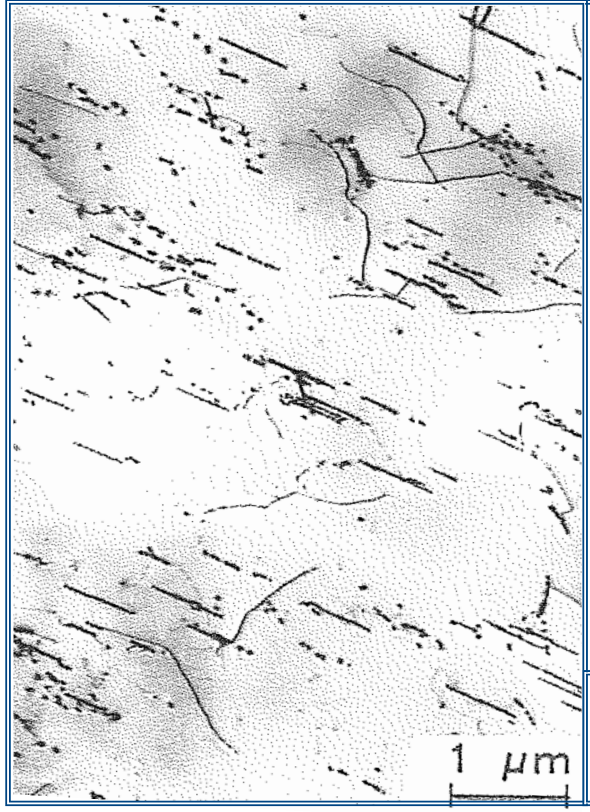


Microstructural experiments performed at ULiège 2023
- Optical microscopy
- macro-indentation (HV10)
- micro-indentation (HV 0.5)
- SEM/EDX

Predicted creep v/s time curve



- Carbide strengthening
  - Presence of Nb, Cr & Ti carbides
  - Dislocations are pinned
  - → Diffusional-driven creep occurs



MC carbides precipitating into dislocations after 30 min at 800°C

TEM image after:
A. Cyrska-Filemonowicz et al., ICEM 13, 1994

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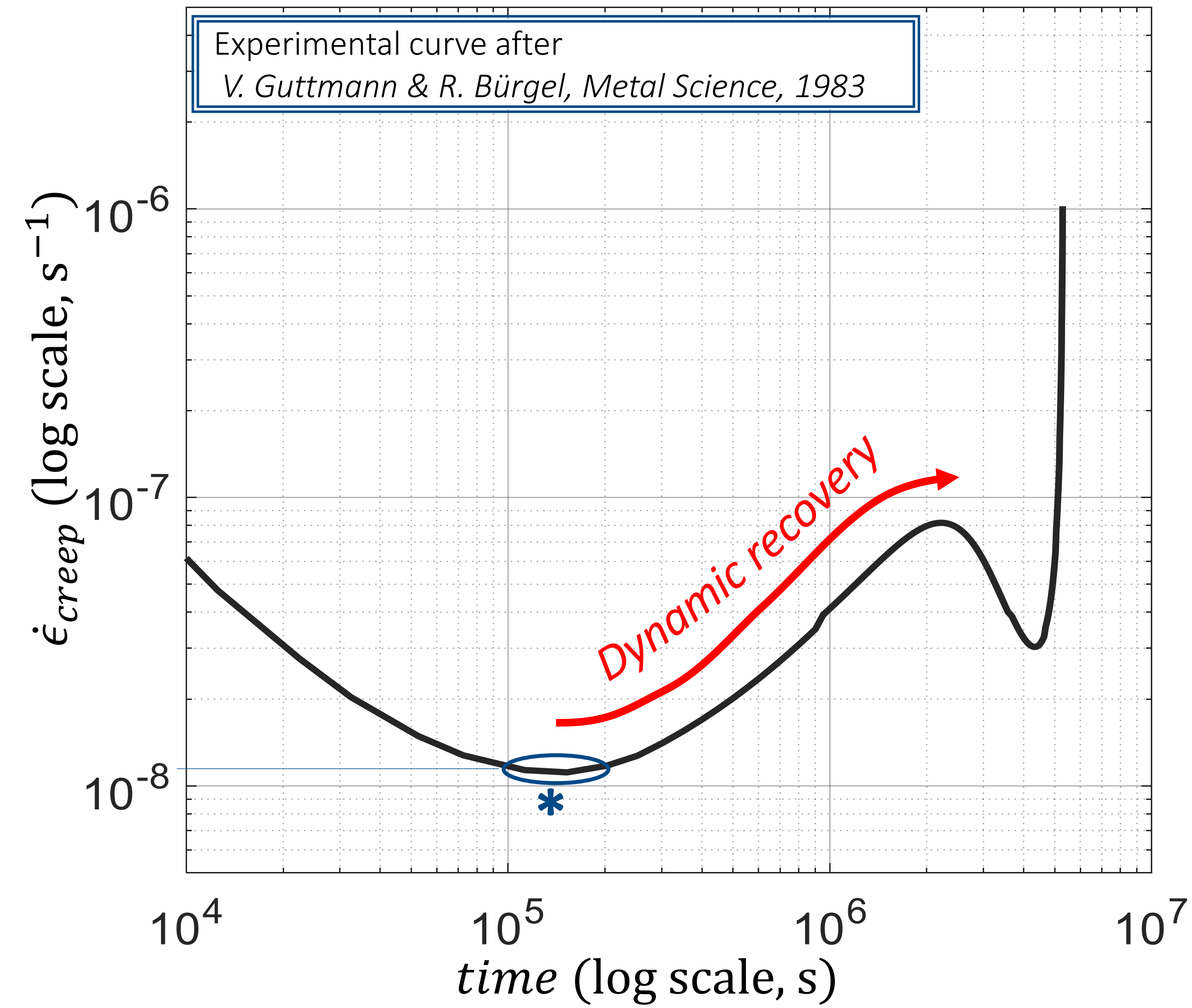
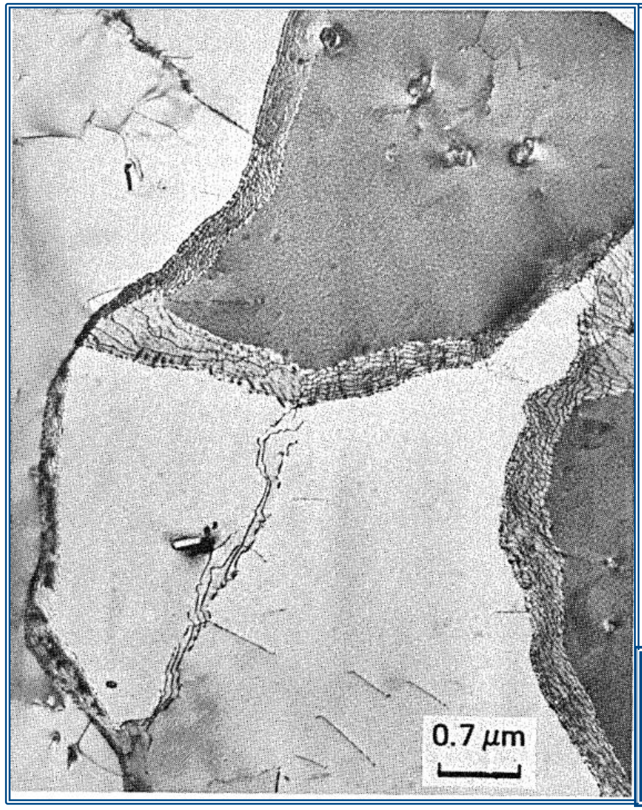
Predicted creep v/s time curve



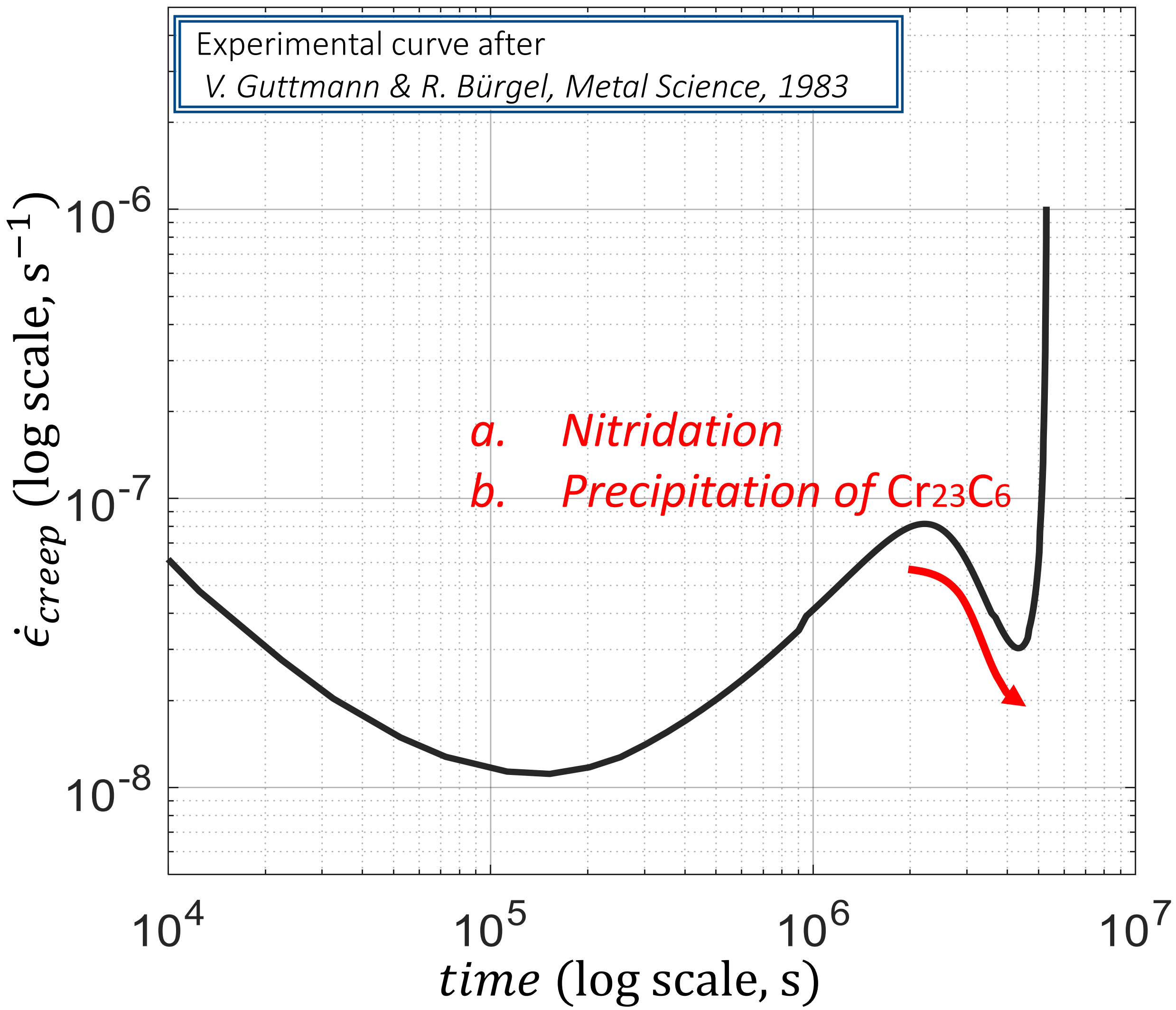
- **Dynamic recovery**
  - MC Carbides diffuse towards GBs
  - Dislocations are able to move freely
  - → Dislocation-driven creep occurs



Dislocation pile-up in GBs of 800H alloy after **minimum creep strain rate*** is reached

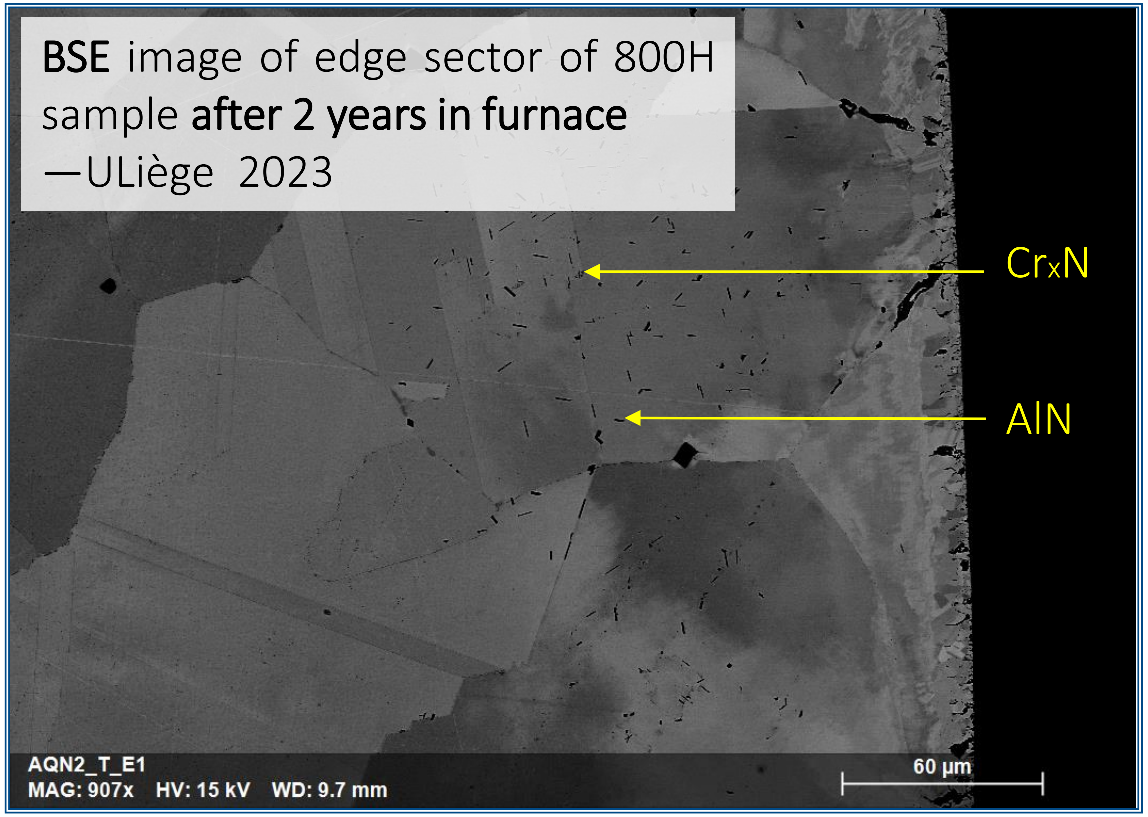
TEM image after
V. Guttmann & R. Bürgel, Metal Science, 1983

Predicted creep v/s time curve



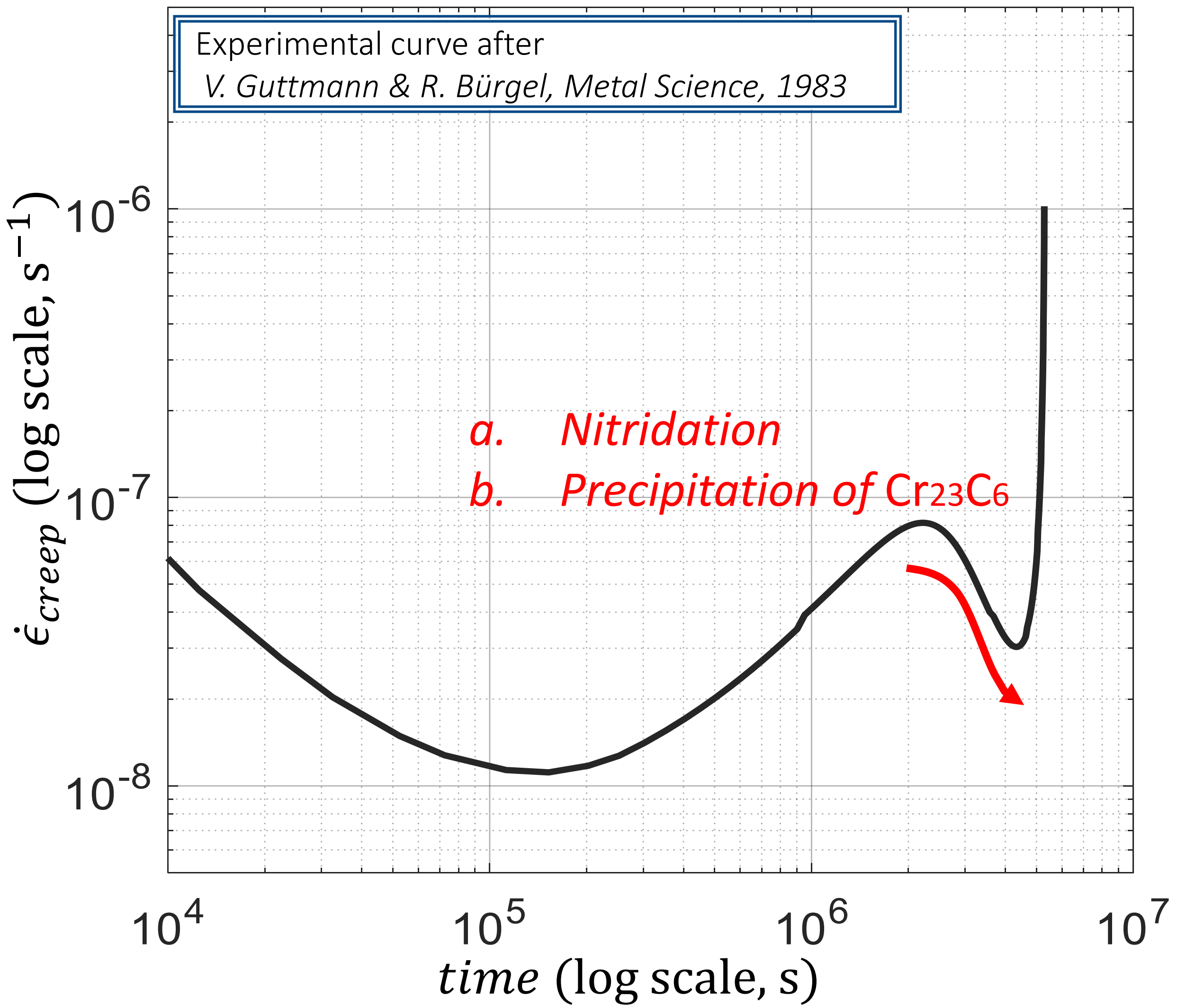
a. Nitridation
- Intragranular precipitation of Cr- & Al- nitrides
- Material surface hardening

→ Nitridation-induced creep hardening



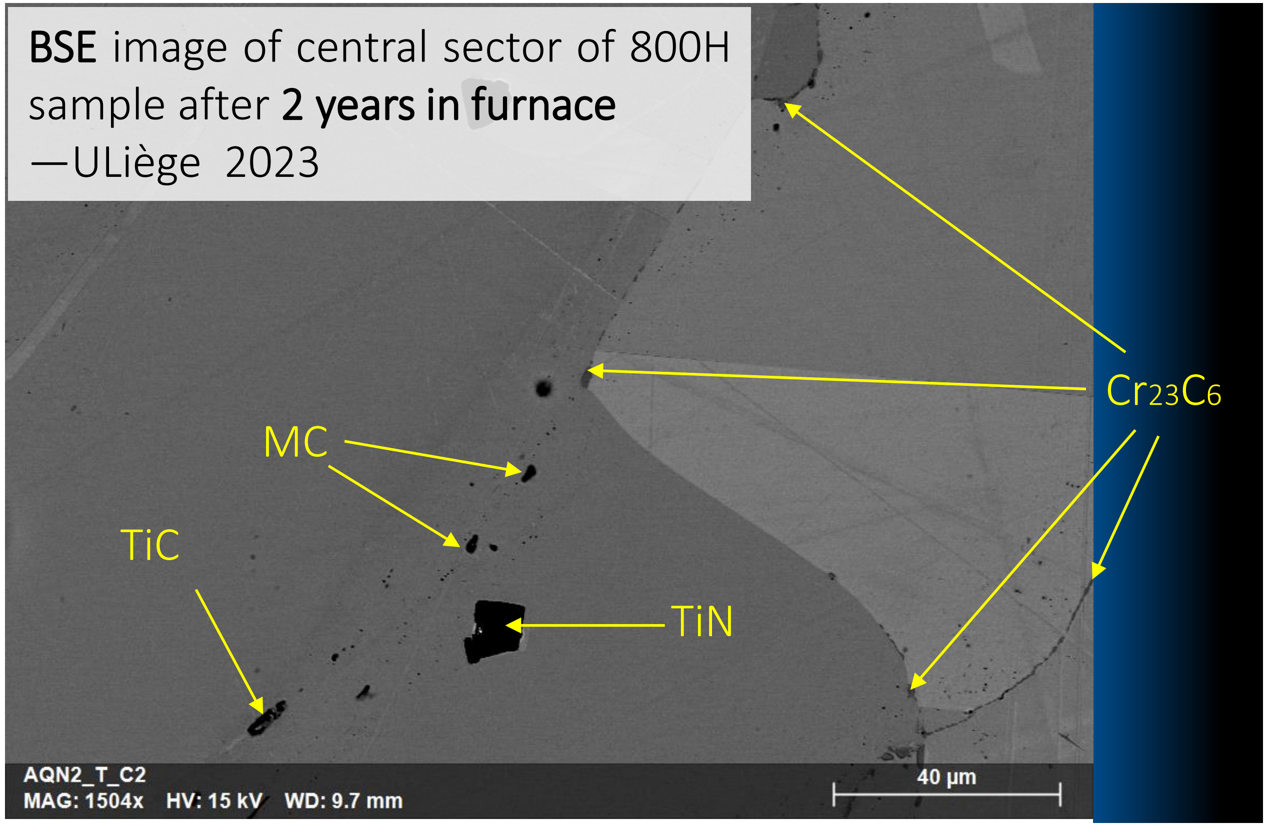
800H creep micromechanics

Predicted creep v/s time curve

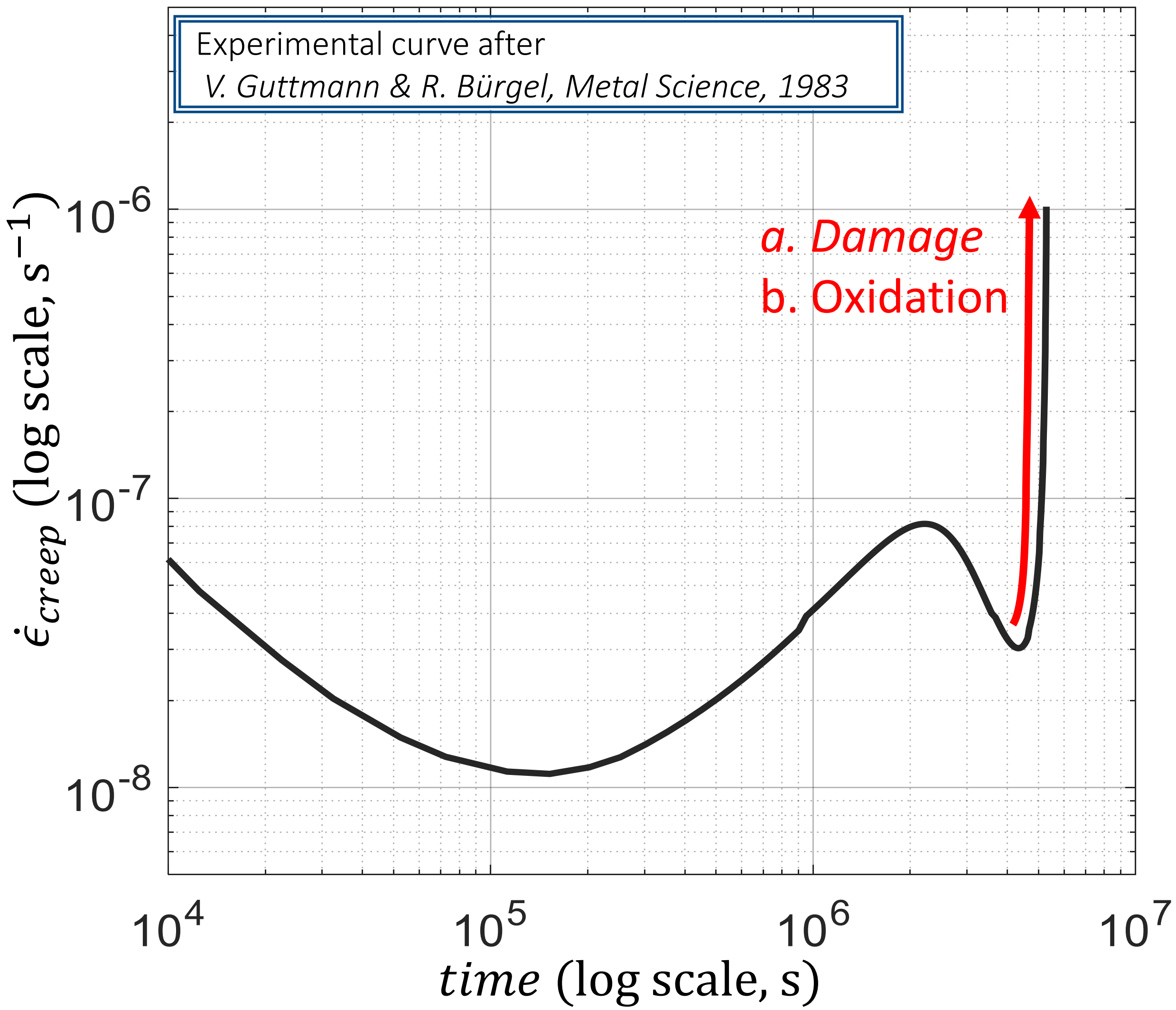


b. Precipitation of $Cr_{23}C_6$ carbides

- Intergranular precipitation of $Cr_{23}C_6$ carbides
  → Grain boundary particle strengthening



Predicted creep v/s time curve



a. Damage: grain decohesion

- Intragranular void formation within triple joints
- Void growth at grain boundary

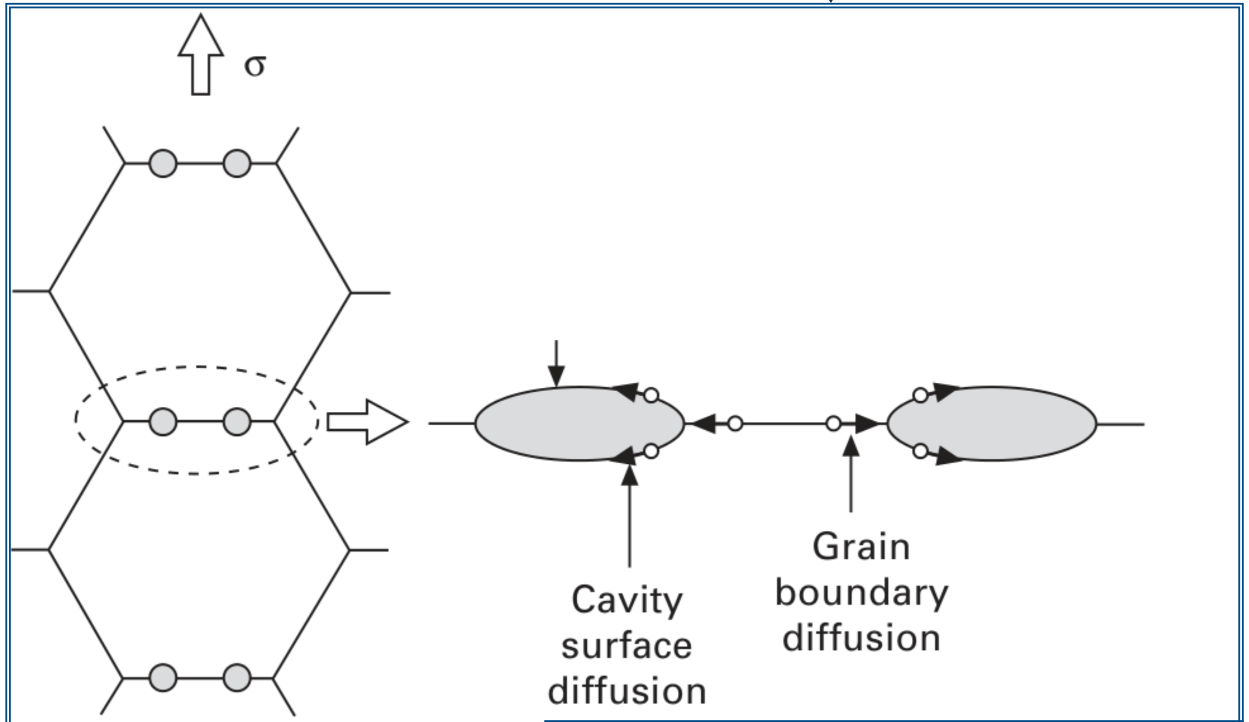
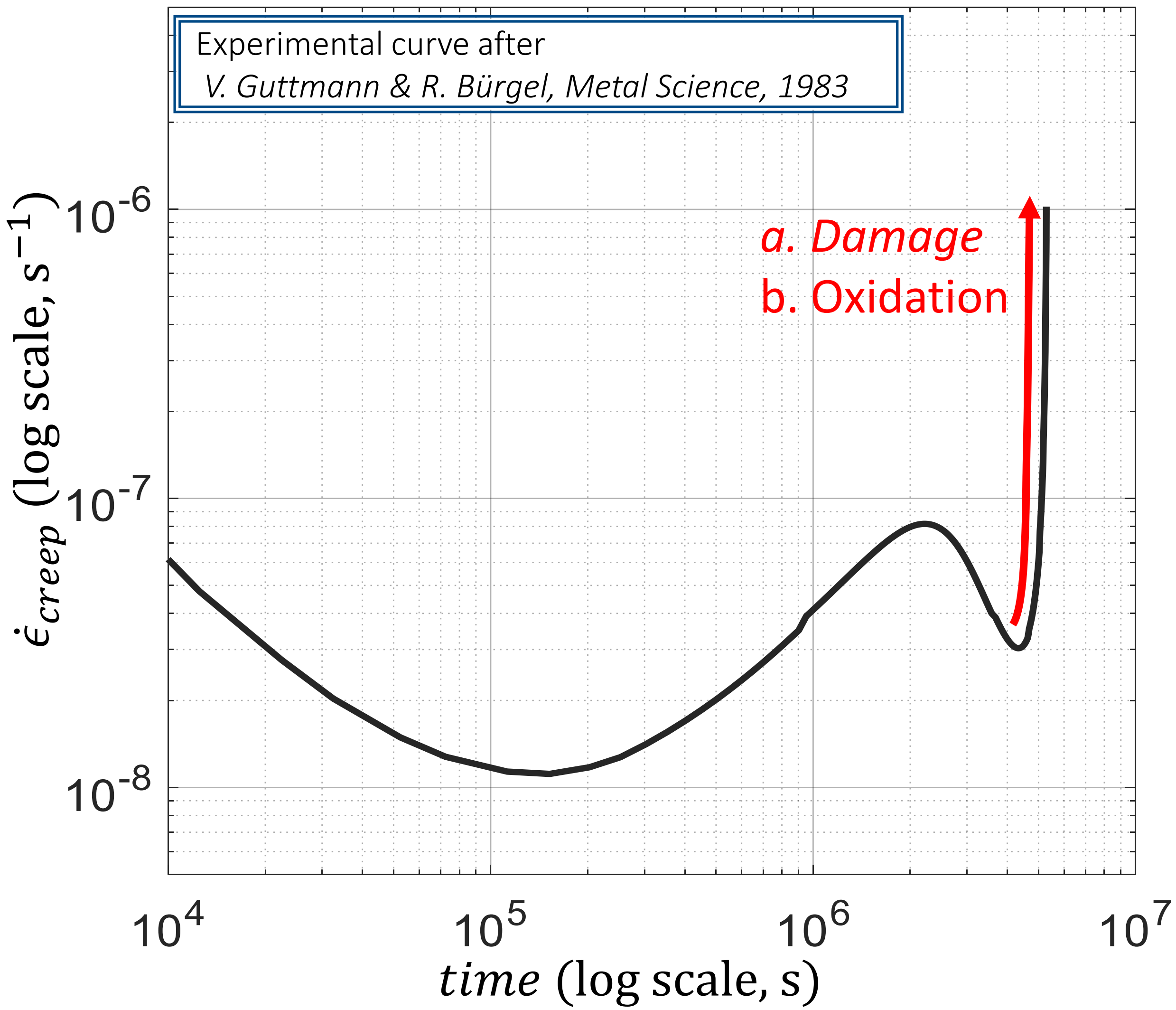


Illustration after
K. Maruyama, Creep Resistant Steels, Ch.12

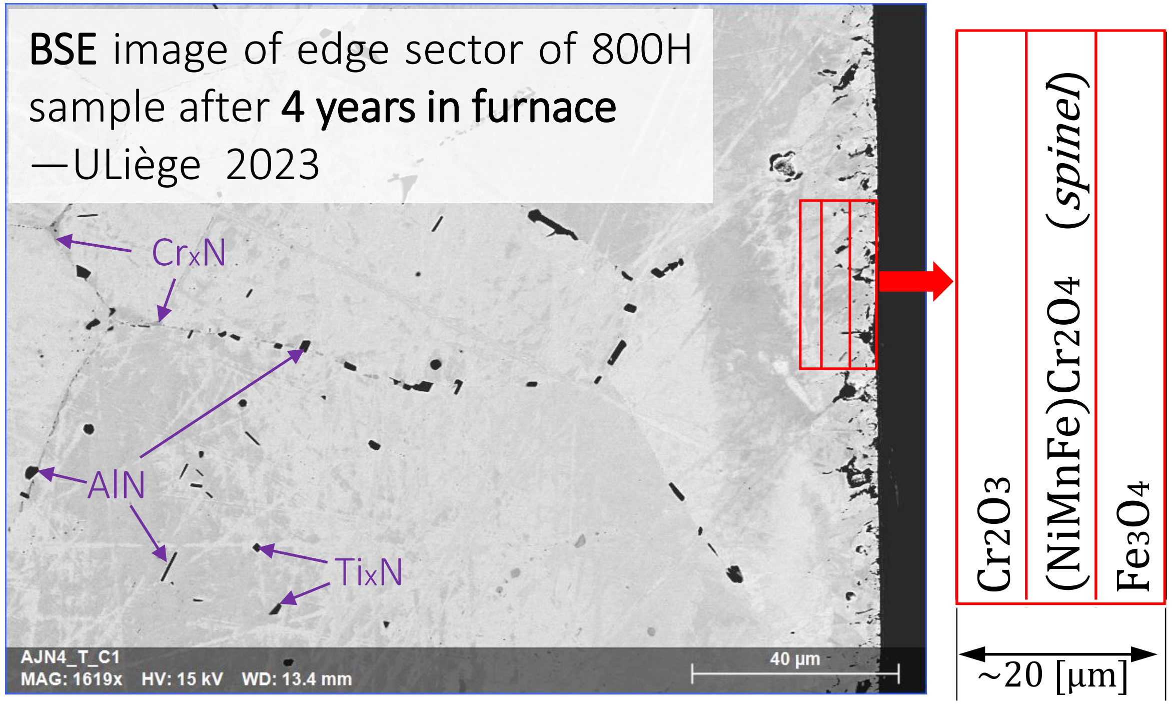
800H creep micromechanics

Predicted creep v/s time curve



b. Oxidation

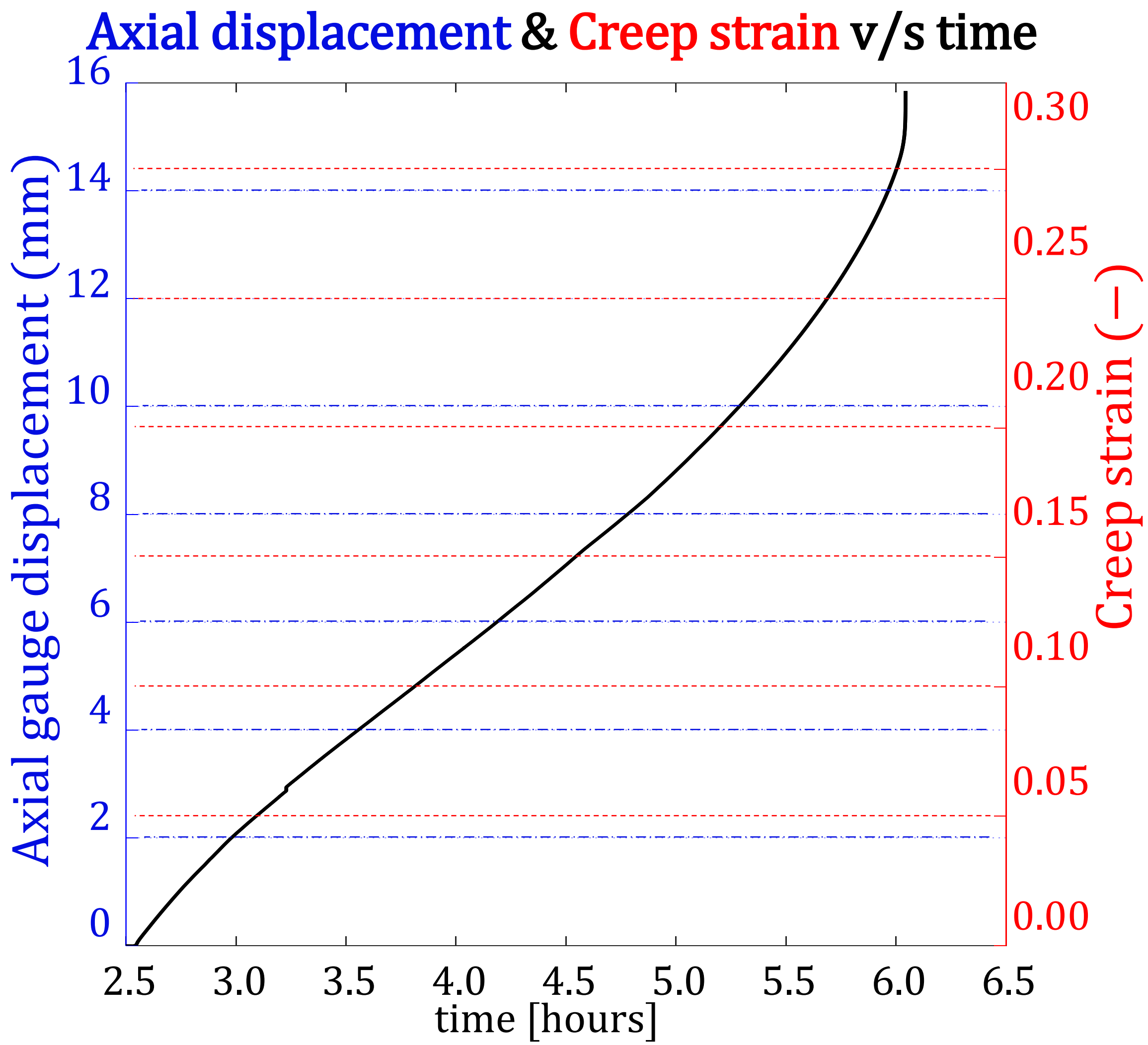
- Depleted Cr-zones due to nitridation enable deeper penetration of Fe, Mn & Cr oxides
  - ➢ Favors intragranular fracture propagation

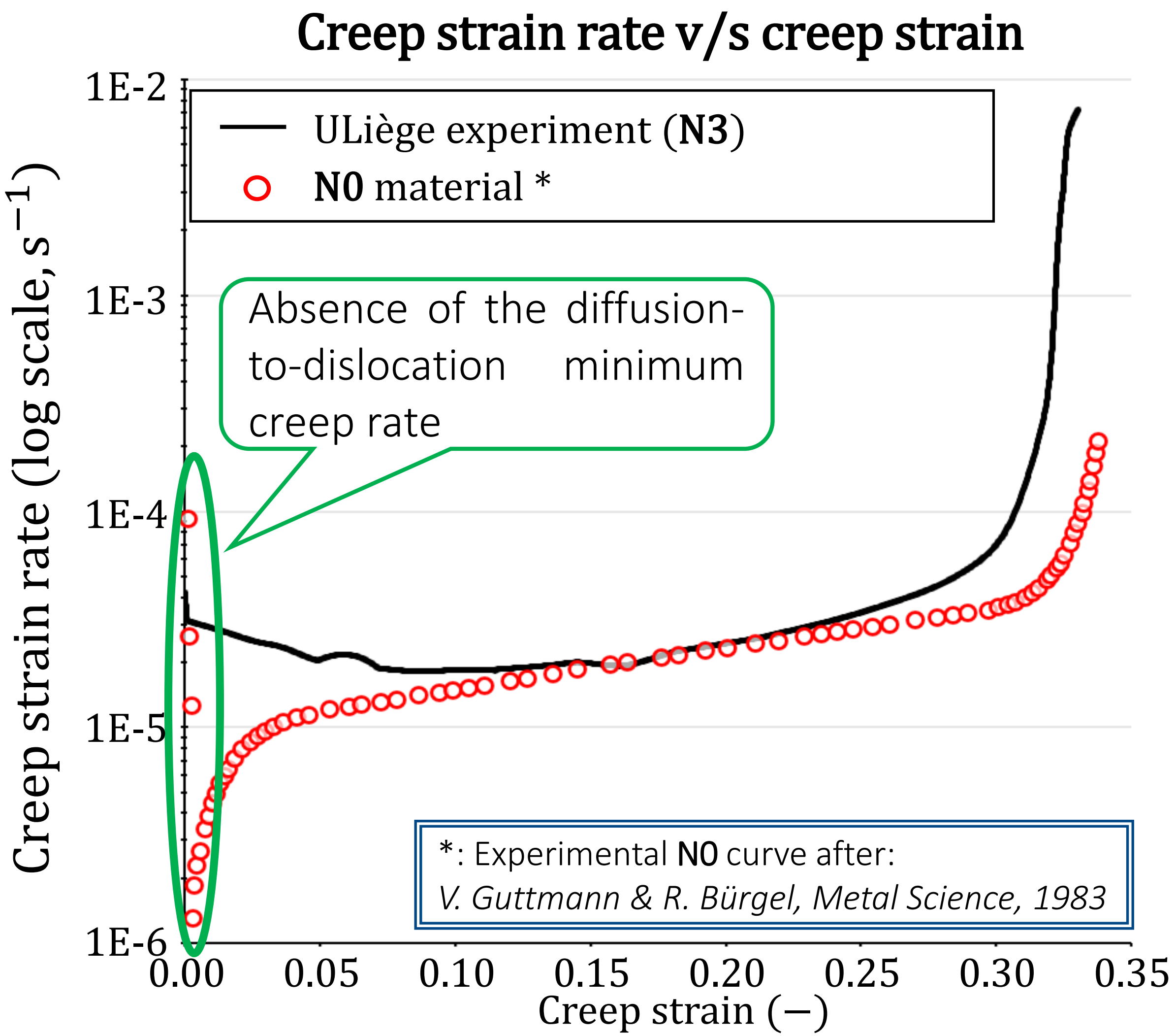


BSE image of edge sector of 800H sample after **4 years in furnace** —ULiège 2023

Experimental findings

800H creep test on sample N3 (3 years in-furnace): 1000°C & 35 [MPa]





Creep in 800H: a multiscale phenomenon

Diffusion-driven creep

Dislocation-driven creep

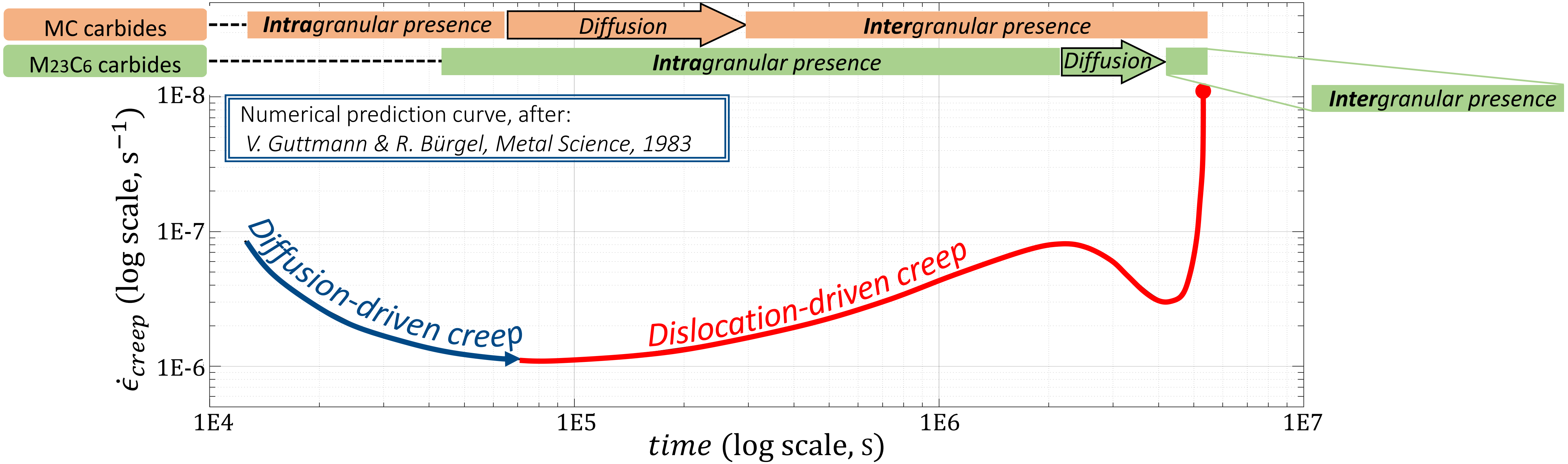
Creep micromechanics

800H microstructure

T° + time	MC carbides	M23C6 carbides
T° + environment + time	Cr & Al nitrides	Cr, Fe & Mn oxides

Creep macromechanics

Creep rate v/s time (log. Scale) curve for 800H exhibiting non-classical behaviour



Creep in 800H: a multiscale phenomenon

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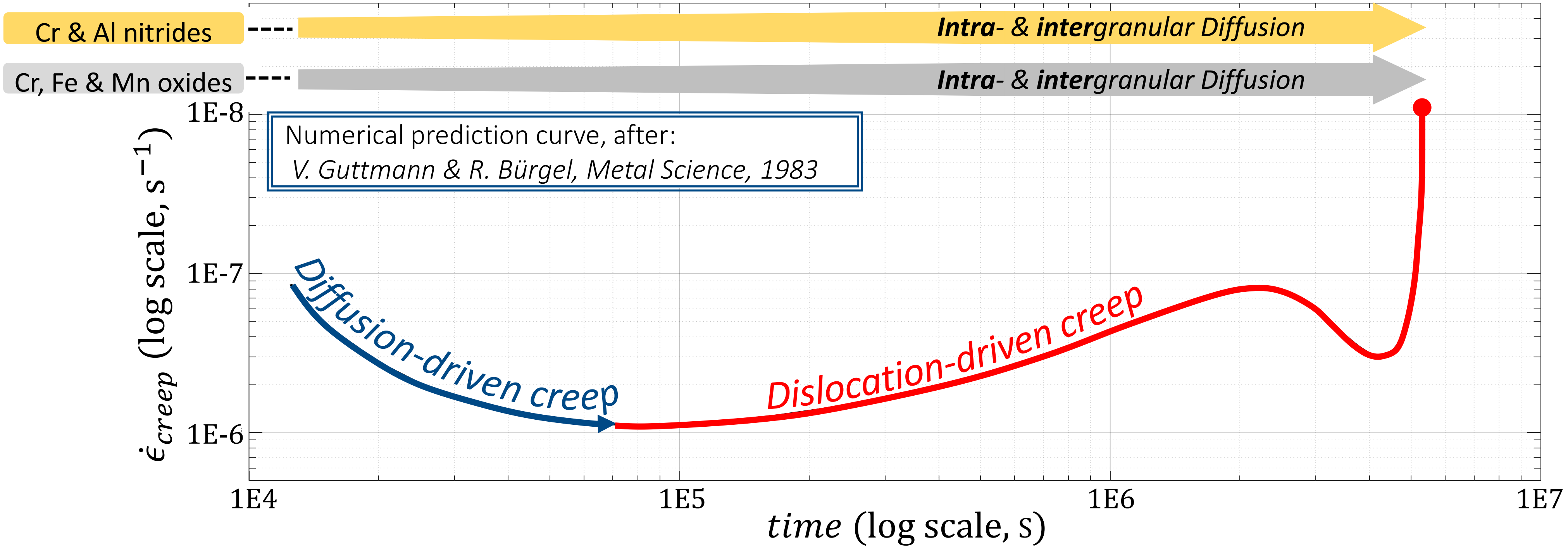


Multiscale correlation

Creep in 800H: a multiscale phenomenon

Diffusion-driven creep

Dislocation-driven creep

Creep micromechanics

800H microstructure

T° + time	MC carbides	$M_{23}C_6$ carbides
T° + environment + time	Cr & Al nitrides	Cr, Fe & Mn oxides

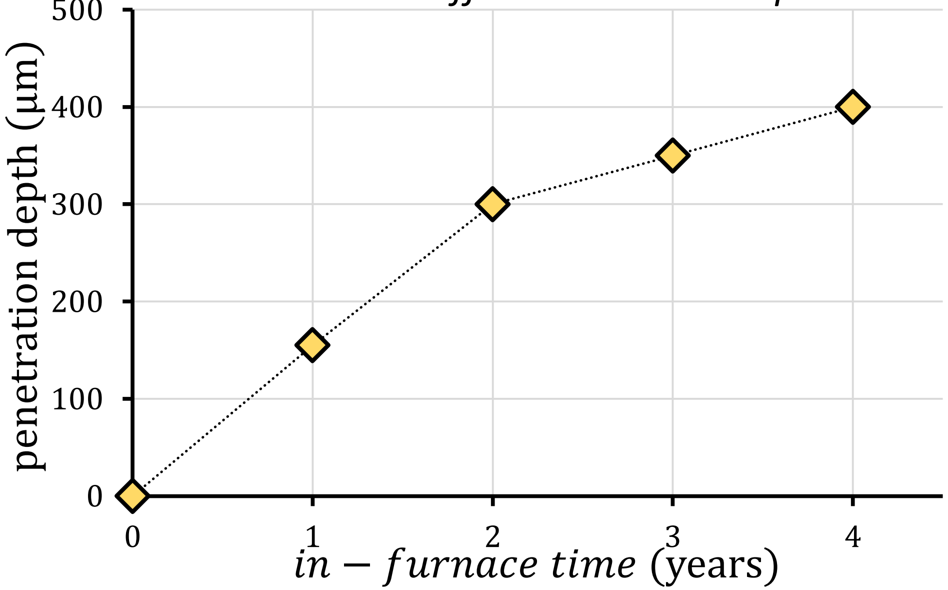
Creep macromechanics

Cr & Al nitrides ---- ***Intra***- & ***inter****granular Diffusion*

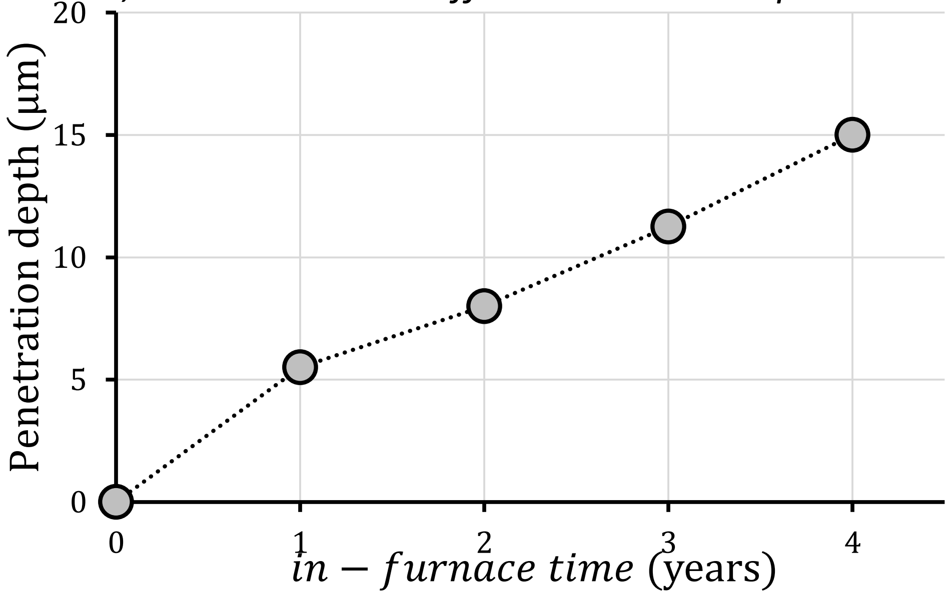
time

Cr, Fe & Mn oxides ---- ***Intra***- & ***inter****granular Diffusion*

Cr & Al ***nitrides*** *diffusion into 800H specimens*

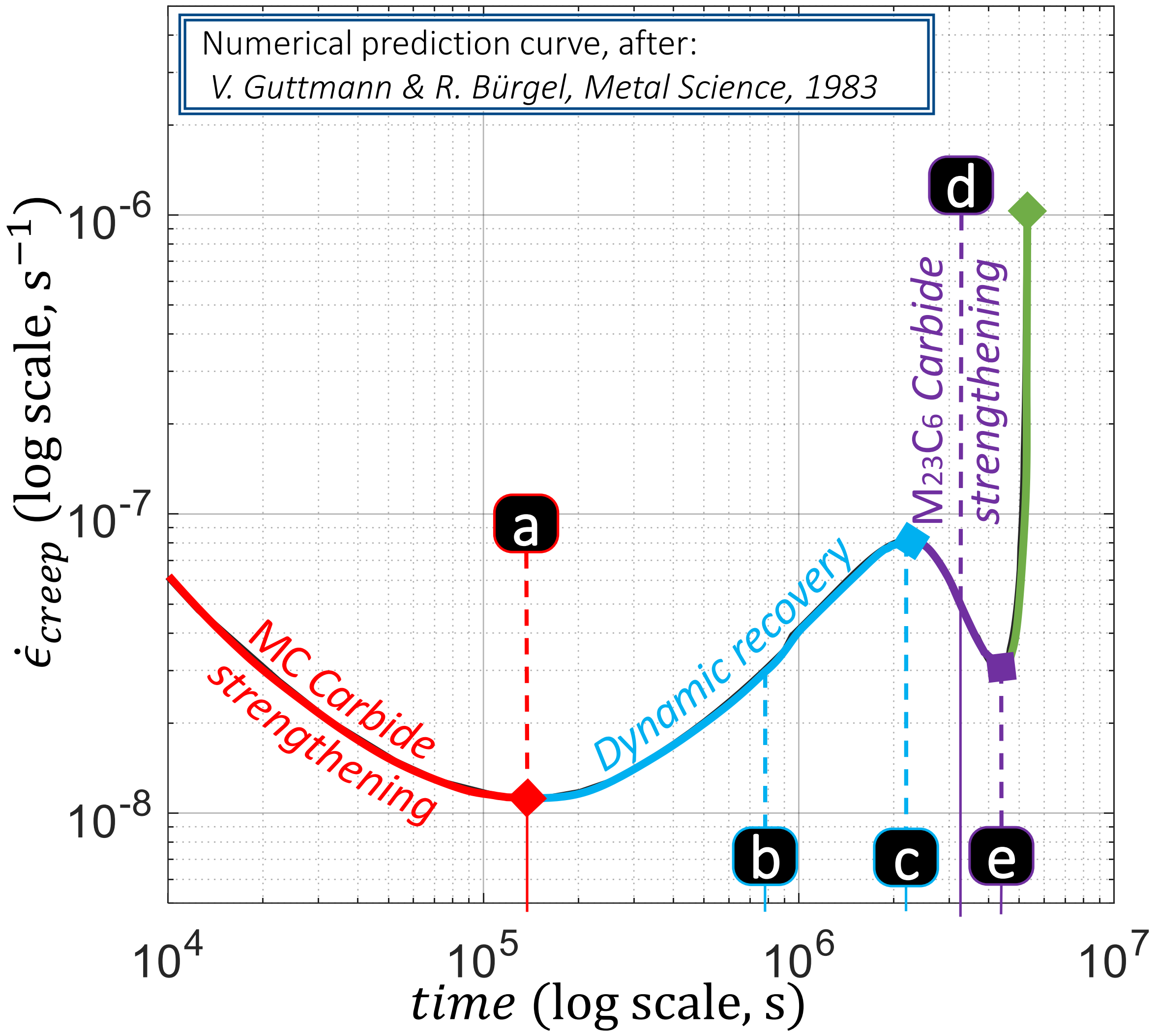


Cr, Fe & Mn ***oxides*** *diffusion into 800H specimens*



Multiscale correlation

Predicted creep v/s time curve



Experimental campaign prospects

Micro characterization

Ascertain **kinetics** of
- MC carbides
- $M_{23}C_6$ carbides
- Cr_x- and Al- nitrides
- Cr-, Mn- & Fe- oxides

Study particle-dislocation interactions

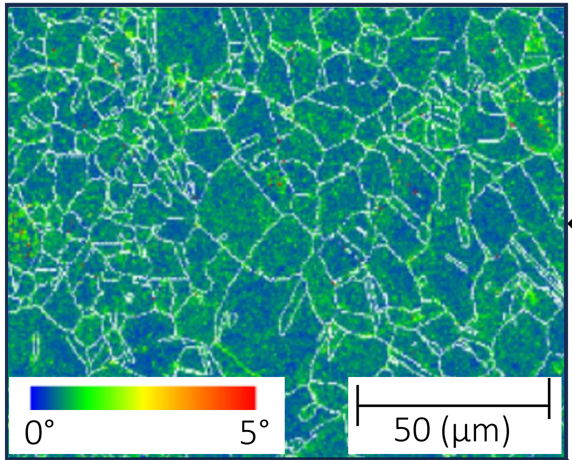
Study nitridation-oxidation interaction

Methodology

Perform [FESEM, EDX, TEM, EBSD] and creep tests on 800H samples N0, N1, N2, N3, N4 [a, b, c, d, e]

Concluding remarks

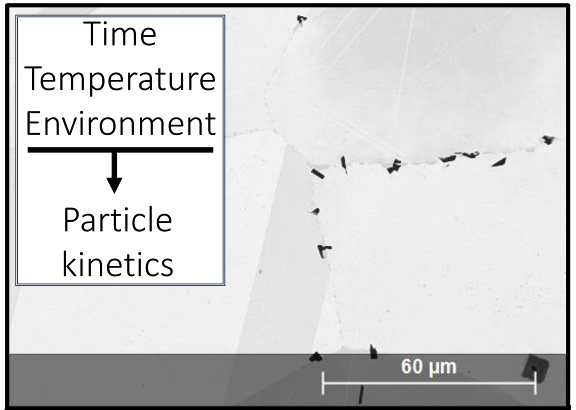
Multiscale modelling: meso-to-macro scale



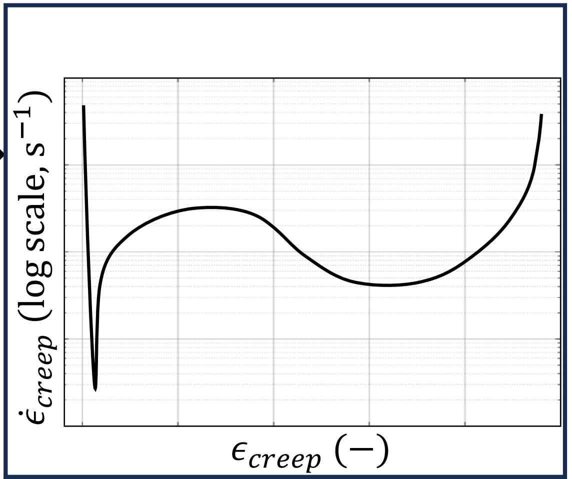
Creep micromechanics

KAM map of austenitic Ni-alloy after:
T. Hatakeyama, Mater. Sci. Eng. A, 2022

Time
Temperature
Environment
↓
Particle kinetics



800H microstructure



Creep macromechanics

Numerical modelling

Development

Mesoscale modelling
- Constant microstructure
- Or evolving microstructure
- Precipitate kinetics
- Diffusion & dislocation creep

Validation

Simulation of real tests and results analysis

Prospects

Generation of reliable virtual tests for better identification, better modelling

Creep mechanisms of Incoloy 800H at high temperature

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July 3rd, 2023

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Project funded by FRIA grant 4000-8987

Post Doc position - Horizon Europe project about Creep Experiments and Modelling

As partner of the European project entitled

AI powered characterization and modelling for green steel technology ,

the MSM Materials and Solid Mechanics team led by prof. L. Duchêne and AM Habraken is recruiting a Post-Doc researcher (a salary, not a grant).

Duration: 3 years, starting on 1 September 2023,

anne.habraken@uliege.be