MSM

M.M.S
Metallic Materials Science

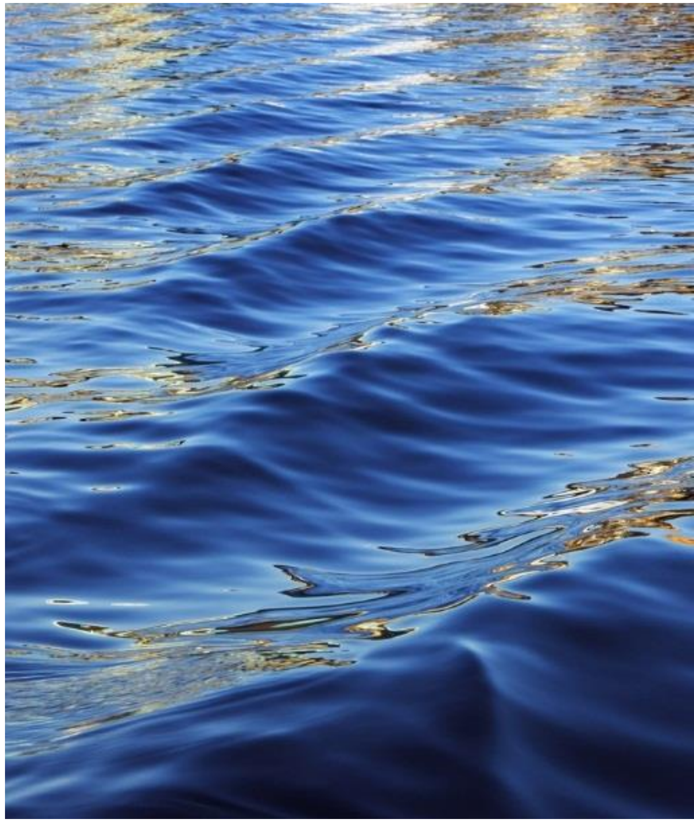
LIÈGE université
Sciences Appliquées

A creep survey:
from creep mechanisms to macroscopic and microscopic models

AM Habraken,

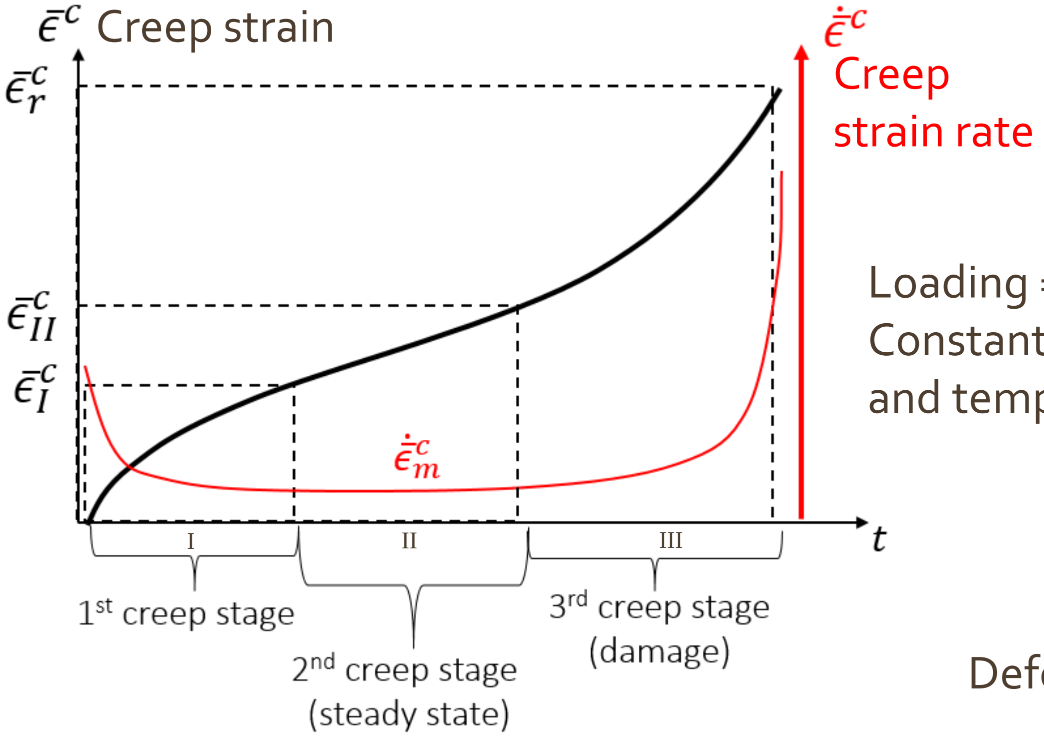
G. Bryndza, F. Chen, L. Duchêne, A. Mertens,

C. Rojas, J. Tchuindjang



Toward sustainability
A good design reduces energy consumption, saves raw material

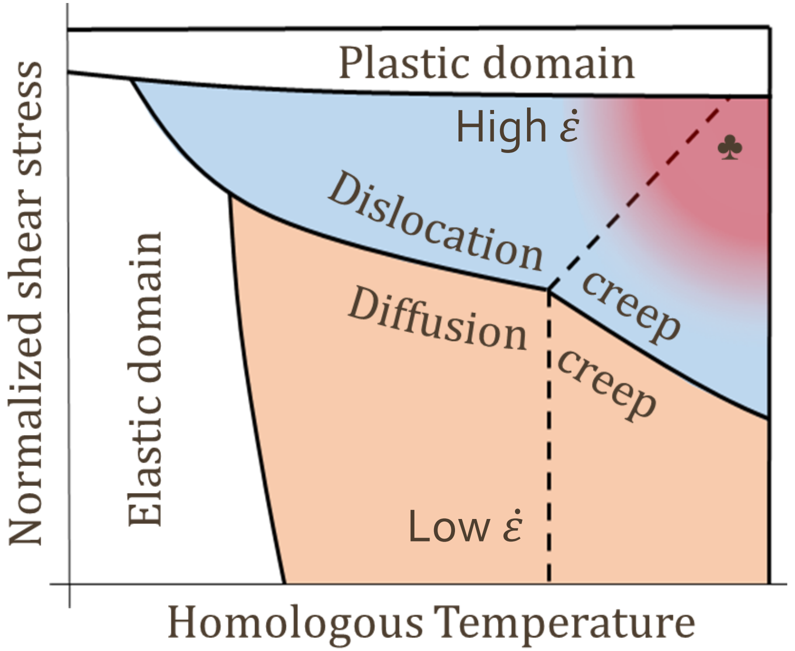
What is creep?



Loading =
Constant stress
and temperature

Typical creep curves

Schematic Deformation
Mechanism Map
4 Regions



♣: Dynamic recrystallization (DRX)

Deformation Mechanism Map

Deformation-Mechanism Maps, The Plasticity and Creep of Metals and Ceramics, by *Harold J Frost*, Dartmouth College, USA, and *Michael F Ashby*, Cambridge University, UK
https://defmech.engineering.dartmouth.edu/

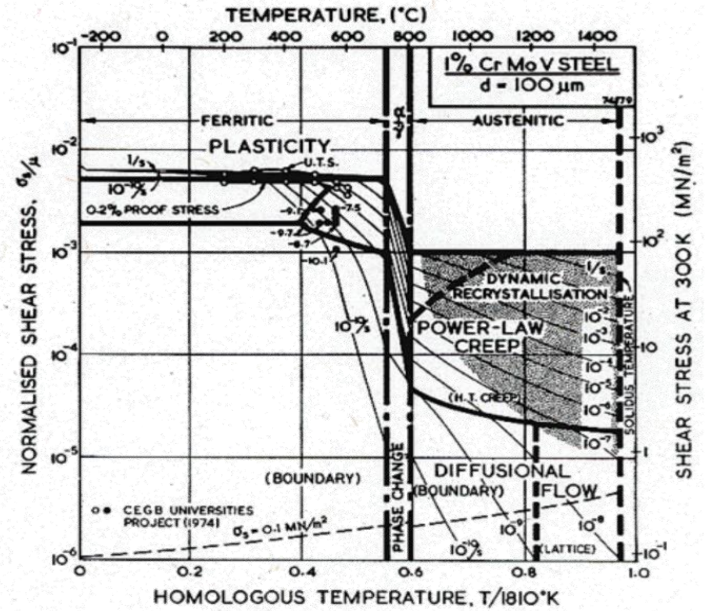


Fig. 8.7. A 1% Cr-Mo-V steel, of grain size 100 µm, showing data.

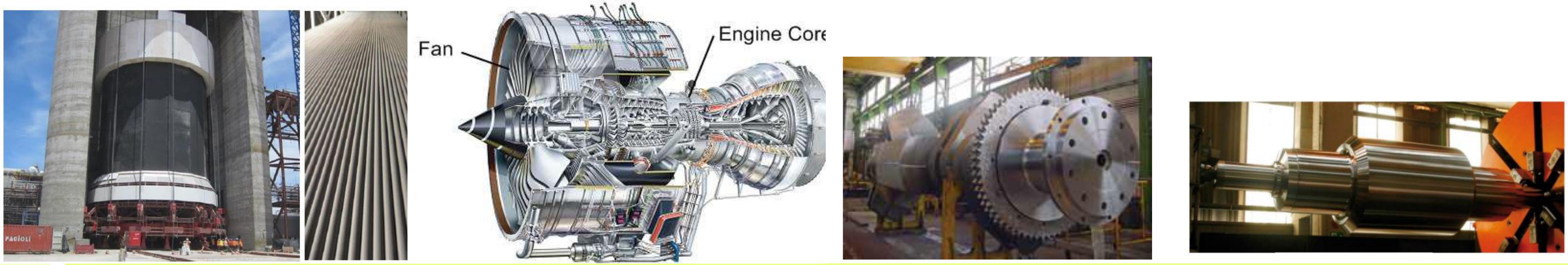
Why is creep studied ?


PETROCHEMICAL industry

- Many sectors have creep issues

- Modeling creep → Correct design of parts
  → Optimal industrial maintenance and investment plan
  → Reduce product development time (validation tests)

- Understanding creep mechanism → Optimal design of alloy composition, heat treatments



SOLAR plant, AERONAUTIC, TRANSPORT , STEEL industry

Contents

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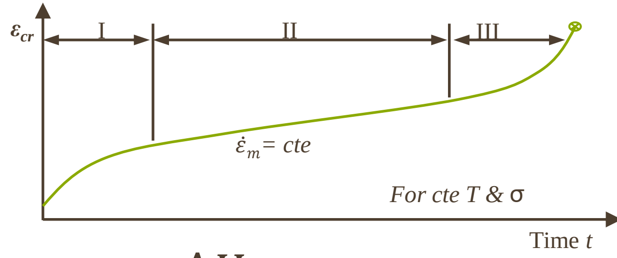
About master curves, Larsen-Miller Parameter LMP



Stationary creep （power law):

$$\dot{\varepsilon} = B\sigma^n e^{-\frac{\Delta H}{kT}}$$

B and *n* are material constants
Δ*H* is activation energy
n is normally between 3 and 8

Larson and Miller formulation:

$$\dot{\varepsilon} = Ae^{-\frac{\Delta H}{kT}}$$

A is a constant
Δ*H* is activation energy

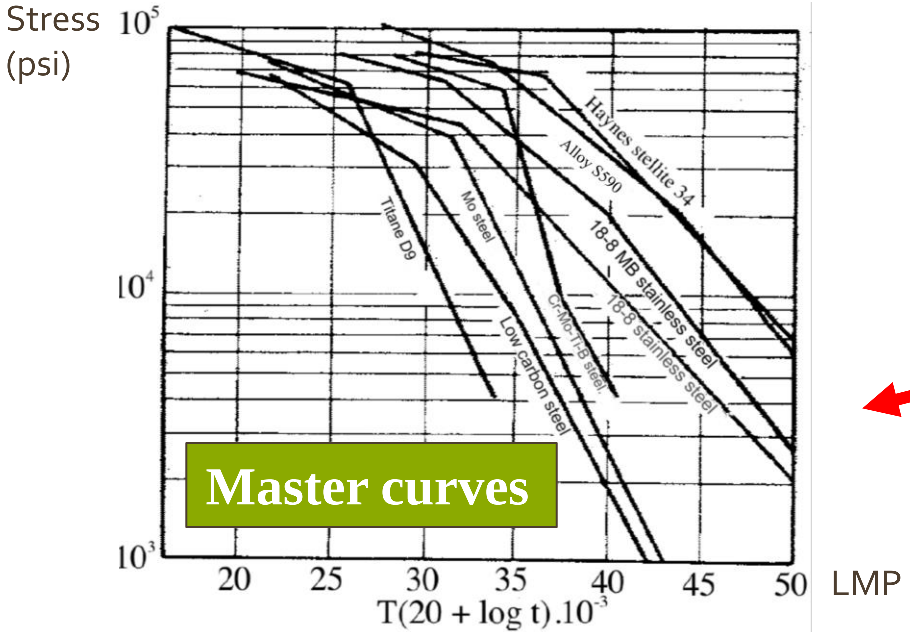
$$\ln\left(\frac{\varepsilon}{t}\right) = \ln\left(Ae^{-\frac{\Delta H}{kT}}\right)$$

$$\ln(t) = \ln\left(\frac{\varepsilon}{A}\right) + \frac{\Delta H}{kT}$$

$$Const = T(\ln(t) + C_1)$$

For most of the alloys $35 < C_1 < 60$

Rupture stress is plotted as
a function of a parameter $(\boldsymbol{x})=\boldsymbol{t_R}$ **or** $\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{m}}$
$T(\ln(\boldsymbol{x}) + C_1)$
As $\dot{\epsilon}_m \cdot t_r = cte$
Monkman-Grant*

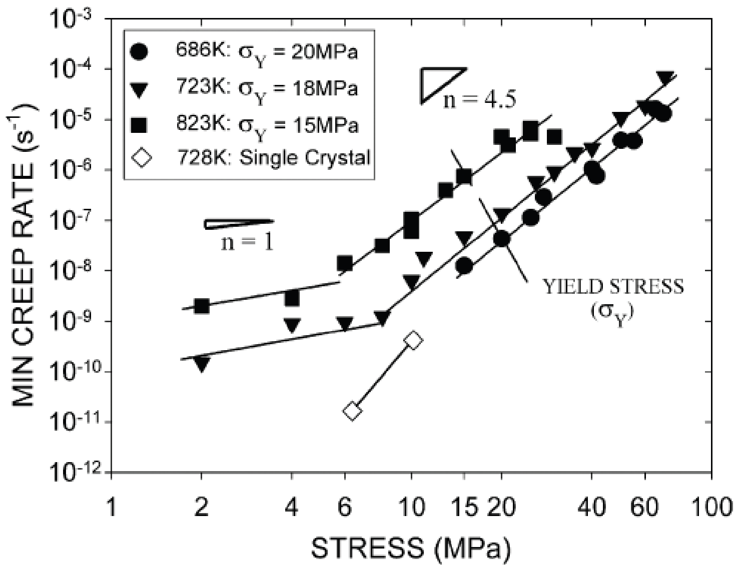


Link σ to $\boldsymbol{T}$ ***and*** $\boldsymbol{t_R}$ **or** $\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{m}}$

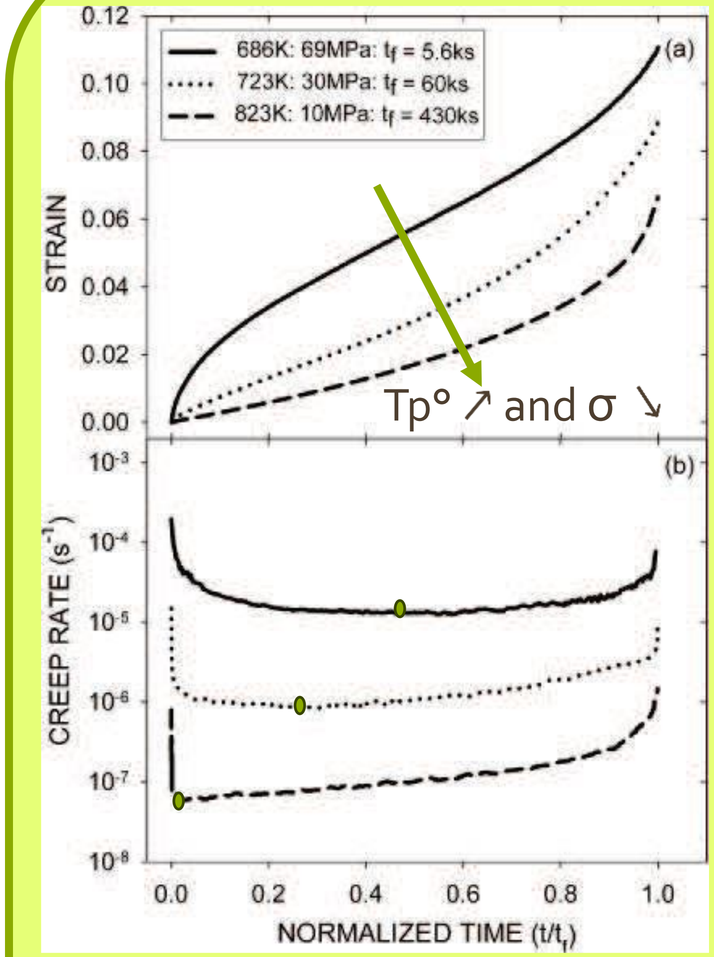
OK for microstructure = cte ⚠

FR Larson, J. Miller, Transactions of the ASME (1954)
GE Dieter, " Mechanical *Metallurgy* ," McGraw-Hill Book Company (1988)

* **Wilshire B, Battenbough AJ. Materials Science and Engineering: A 2007**



≠ n with "no" physical meaning



Experimental creep observations
If Tp° ↗ and σ ↘

Creep state II $\dot{\bar{\epsilon}}_m^c$ ↘
earlier

From power-law analysis there is no indication that creep behavior changes in the higher stress regime.

LMP does not point the correct position of mechanism change diffusion → dislocation

No effect of yield stress

No info on creep curves

(σ= cte T=cte)

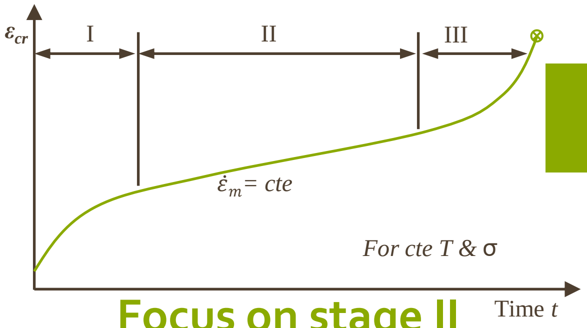
$\varepsilon = f(\sigma, T, t)$

Wilshire introduced the use of σ/σ_Y

And focuses on stade I and III

Wilshire B, Battenbough AJ. Creep and fracture of polycrystalline copper MSEA 2007

Issues of LMP approach and exponential function (Norton)



Focus on stage II

$$\dot{\varepsilon}_m = A\,\sigma^n \exp\left(\frac{-Q_C}{RT}\right)$$

$Q_c\, n$: single constants for different creep regions, **physical meaning is lost**

+ A constant → no effect of yield stress on creep behavior

In experiments : each mechanisms has its kinetic

Wilshire equations (focus on stage I and III)

Based on relative stress = σ/σ_{UTS}

→ Q_c^* related to different physical mechanism depending on creep region

≠ equations ≠ mechanisms → t_r or $\dot{\epsilon}_m^c$

$\dot{\epsilon}_m \cdot t_r = cte$ Monkman-Grant allows to pass from 1->2

$$\sigma/\sigma_{UTS} = exp\left\{-k_1\,[t_r\;\; exp\left(-Q_c^*/RT\right)]^u\right\} \quad (1)$$

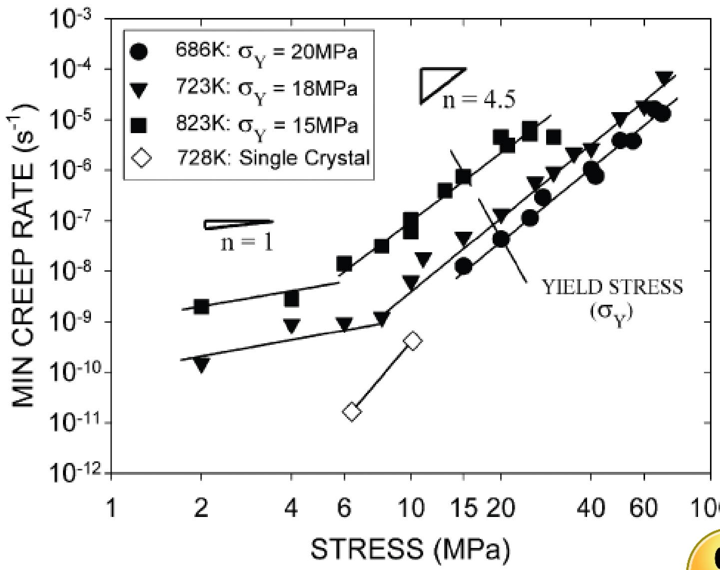
$$\sigma/\sigma_{UTS} = exp\left\{-k_v[\,\dot{\epsilon}_m\; exp\left(-Q_c^*/RT\right)]^v\right\} \quad (2)$$

Whole curve

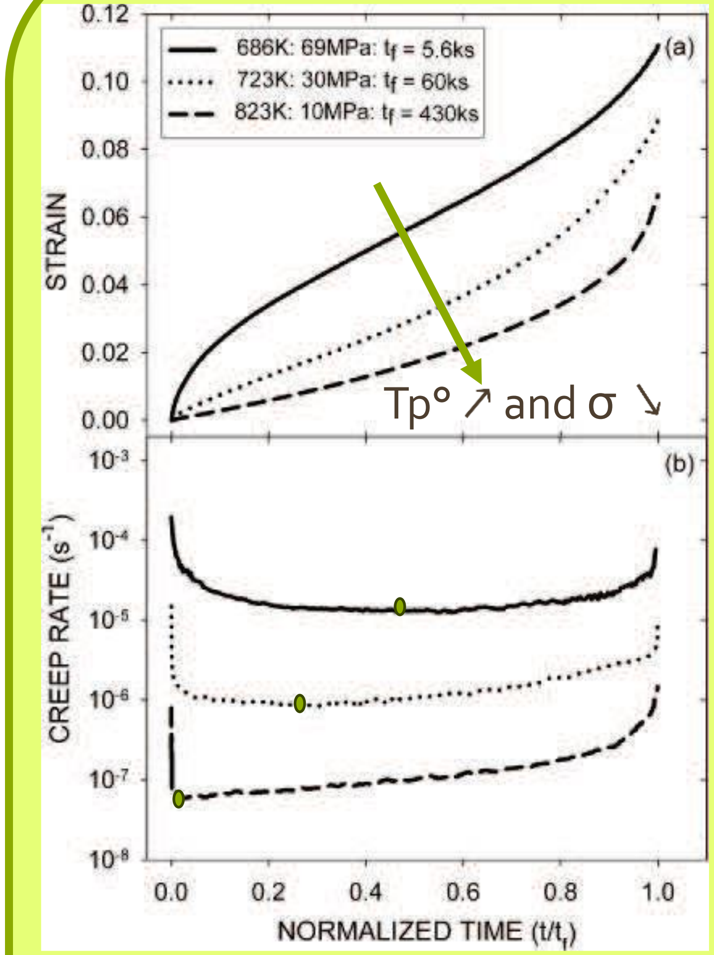
parameters k_w , w = functions of strain

$$\sigma/\sigma_{UTS} = exp\left\{-k_w[t_\varepsilon \cdot exp\left(-Q_c^*/RT\right)]^w\right\}$$

Mark Whittaker et al. Chap 2 Intech open 2018



Norton approach → ≠ **n**

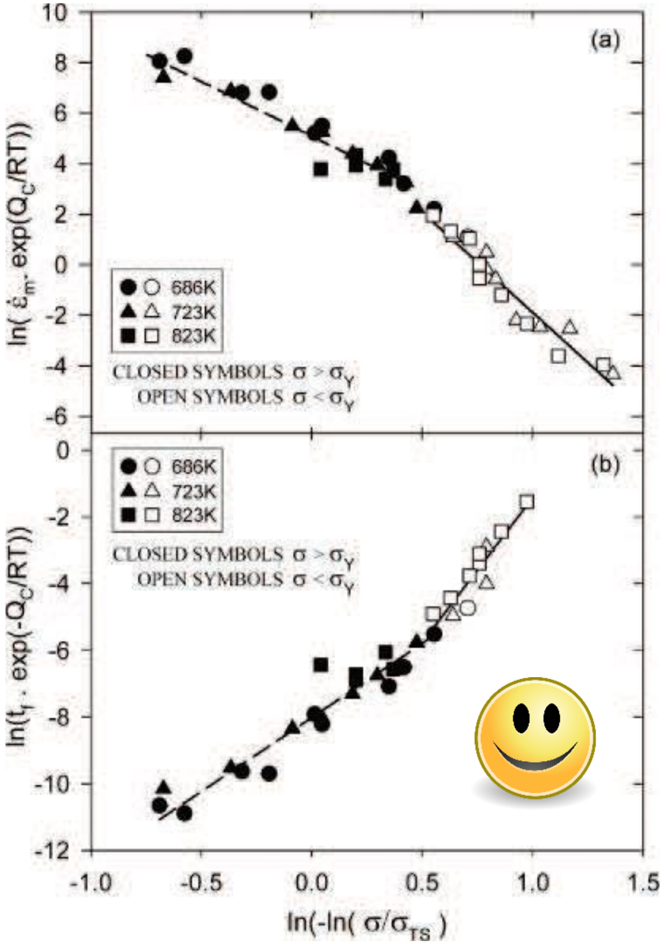


Experimental creep observations

If Tp° ↗ and σ ↘

Creep state II ↘

earlier



Wilshire equations

Q_c^* = cte = grain boundary diffusion

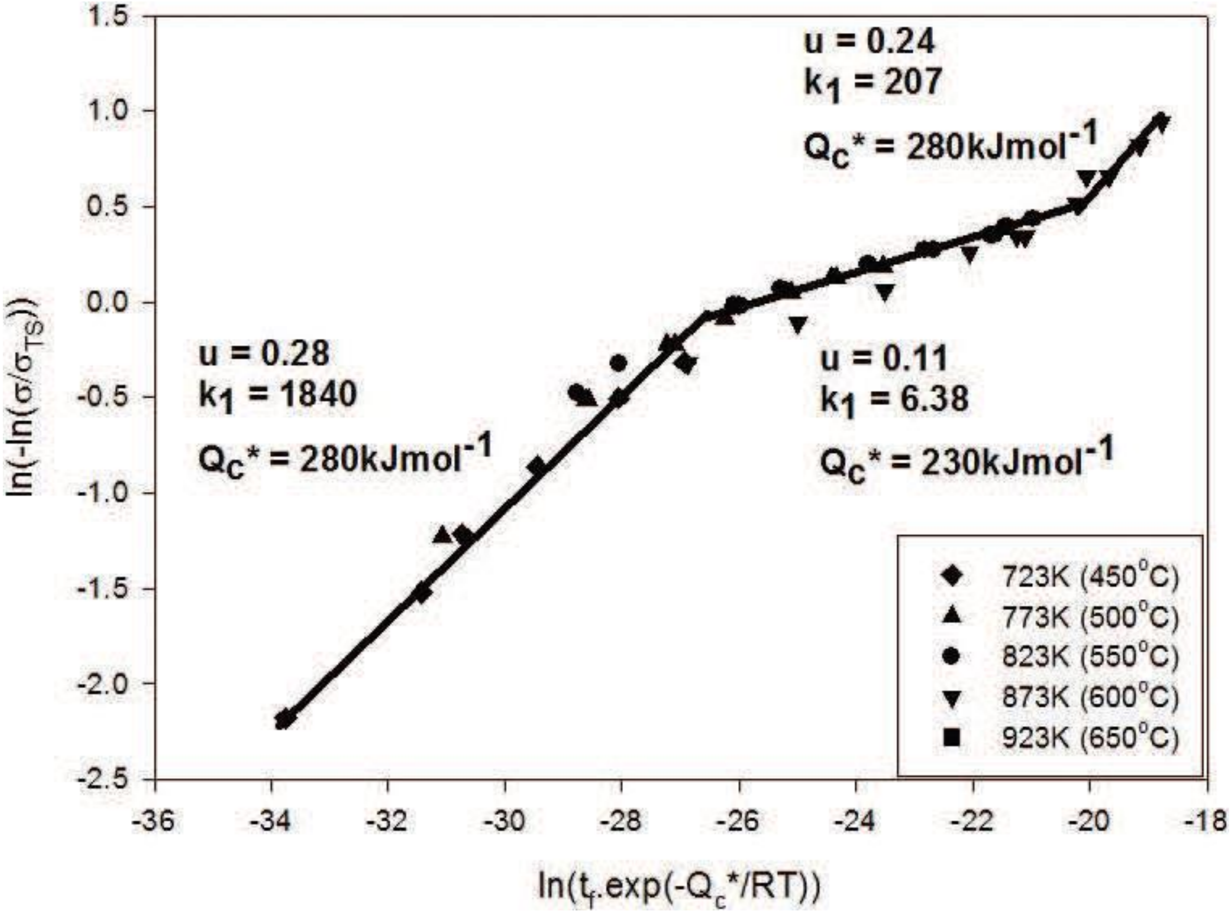
k_i, u, v ≠ for $\sigma < \sigma_y$ and $\sigma > \sigma_y$

$$\sigma/\sigma_{UTS} = exp\left\{-k_u\left[t_f \cdot exp\left(-Q_c^*/RT\right)\right]^u\right\}$$

$$\sigma/\sigma_{UTS} = exp\left\{-k_v\left[\dot{\varepsilon}_m exp\left(-Q_c^*/RT\right)\right]^v\right\}$$

Wilshire B, Battenbough AJ. MSEA 2007

Issues of Wilshire approach



Gr 22 tube
2.25 CR - 1Mo - NIMS data

Wilshire equations
Q_c^* , k_i, u, $v \neq$ multiple ctes

3 Different mechanisms
For 2.25 CR - 1Mo

- High T and long t : bainite degradation → ferrite
- Low σ: mainly GB effect
- High σ: increase of dislocation density

$$\sigma/\sigma_{UTS} = exp\left\{-k_u\left[t_f \cdot exp\left(-Q_c^*/RT\right)\right]^u\right\}$$

$$\sigma/\sigma_{UTS} = exp\left\{-k_v\left[\ \dot{\varepsilon}_m exp\left(-Q_c^*/RT\right)\right]^v\right\}$$

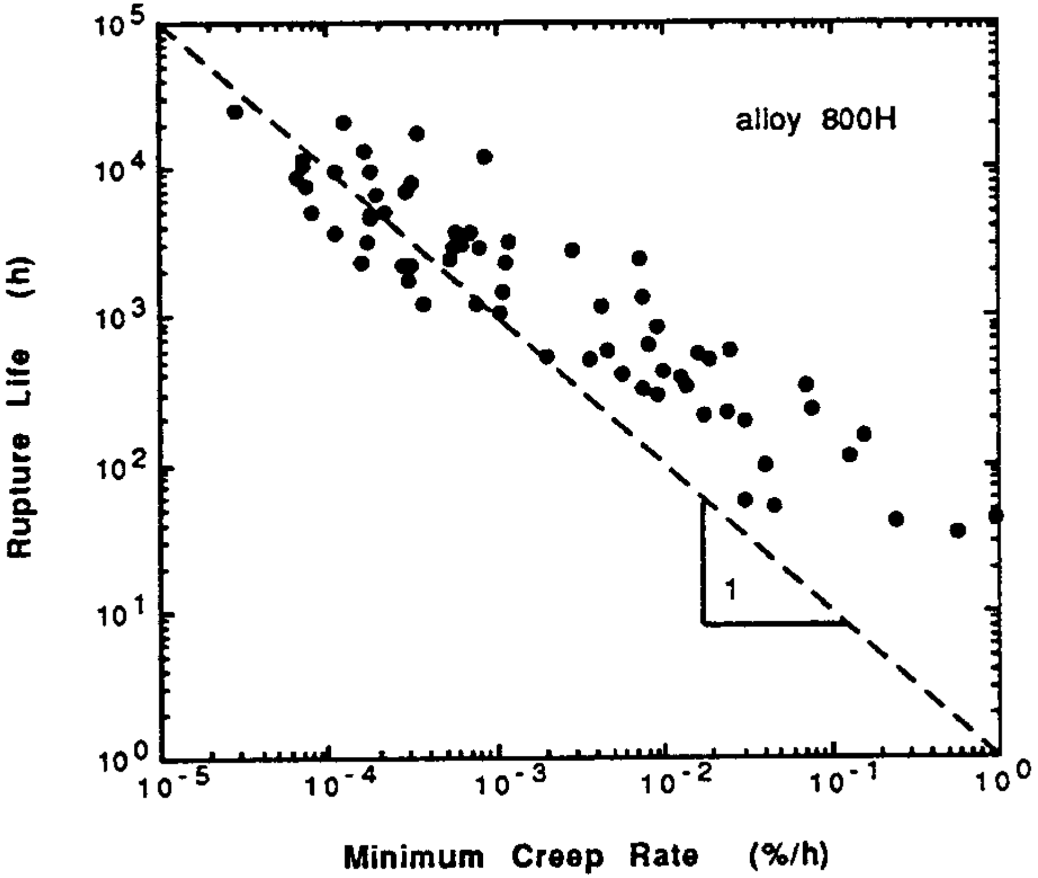
☹

Needs many data
Just scalars $\boldsymbol{t_R}$ **or** $\boldsymbol{\dot{\varepsilon}_m}$ identified
Strong effect of microstructure evolution

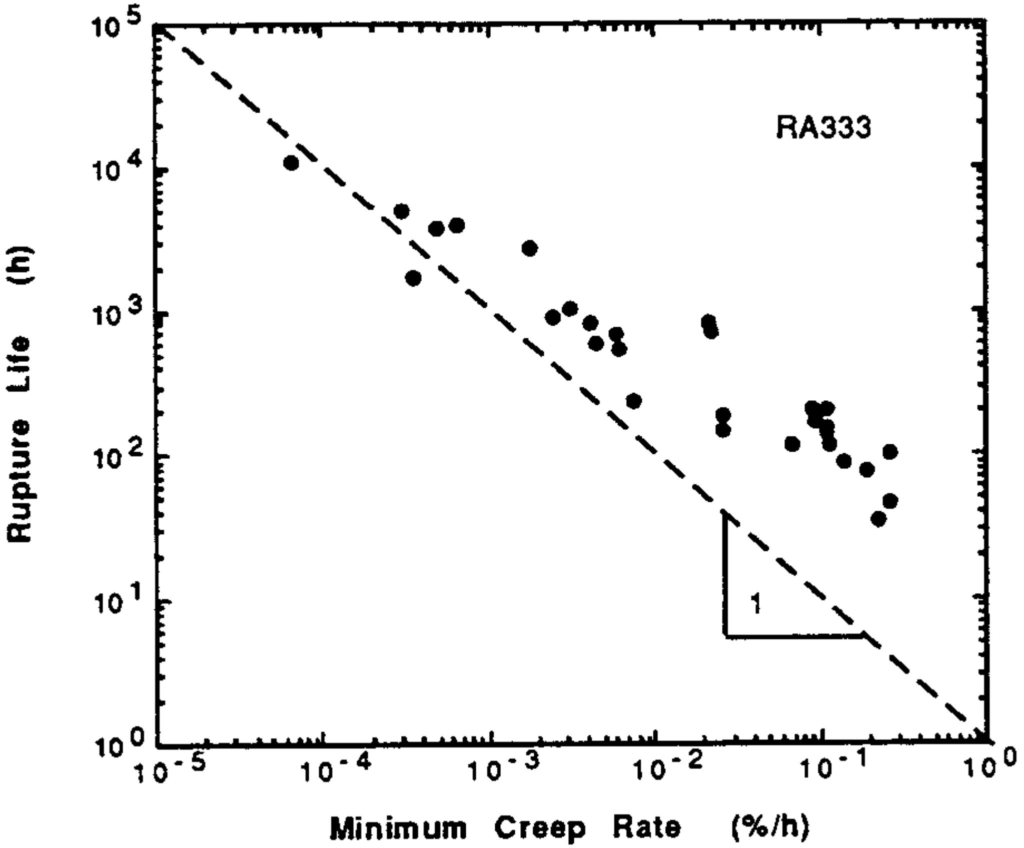
Need to chose correct functions
integrating all information
for FE simulations to model creep
under variable T , σ and long t

Whittaker et al. Chap 2 - Intech creep 2017 Tanski et al

Issue in Monkman-Grant assumption of $\dot{\epsilon}_m \cdot t_r = cte$



Austenitic Incoloy alloy (Fe-Ni-Cr)



Ni-Cr alloy with solid solution strenghtening

Issues in Design of piping and support components in high-temperature fluidized bed combustor systems

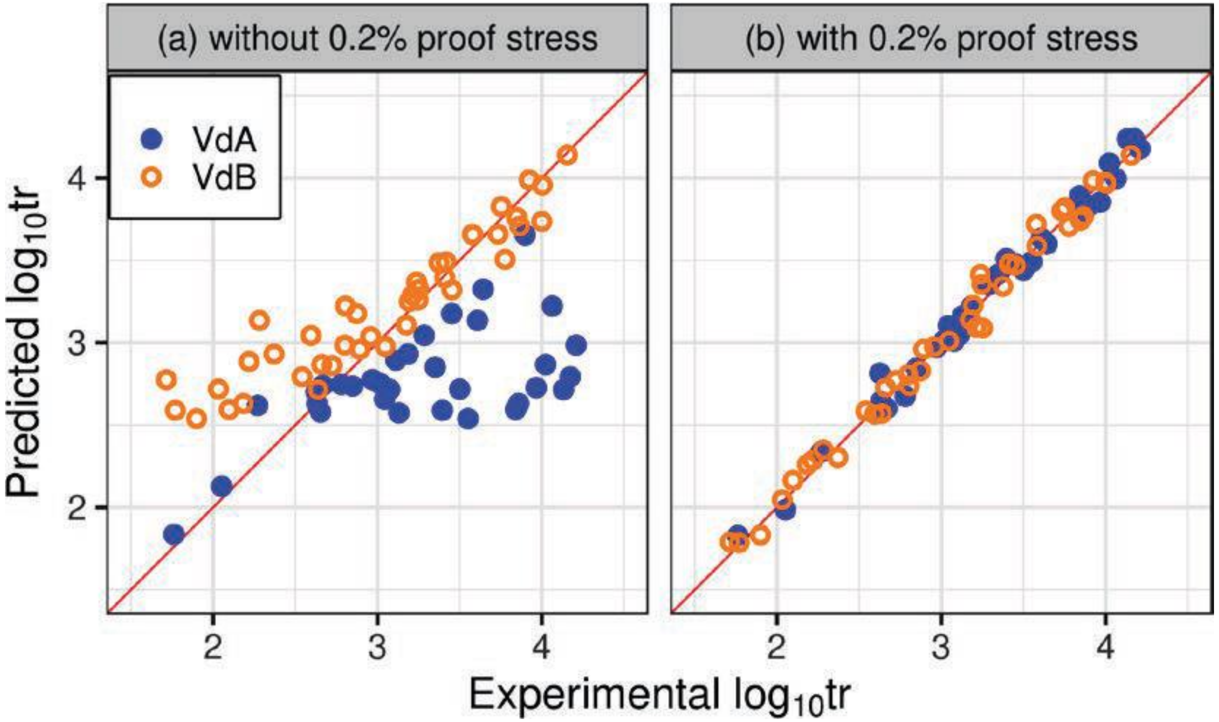
Swindeman RW, Marriott DL. J Eng Gas Turbines Power 1993

Machine learning to predict t_r

Data base used : 27 compositions (ferritic heat resistant steel) a total of 212 creep curves
from carbon steel to low-alloy and high-alloy steels (Fe+ Pe, Fe+Pe+Ba, Ma+Ba) , 0 to 9%Cr

Input: **composition**, test condition (***T, σ***) **+ yield stress σ_y** (to express process manufacturing difference)
Output: log $_{10}t_r$

Validation with or without yield stress included in the training



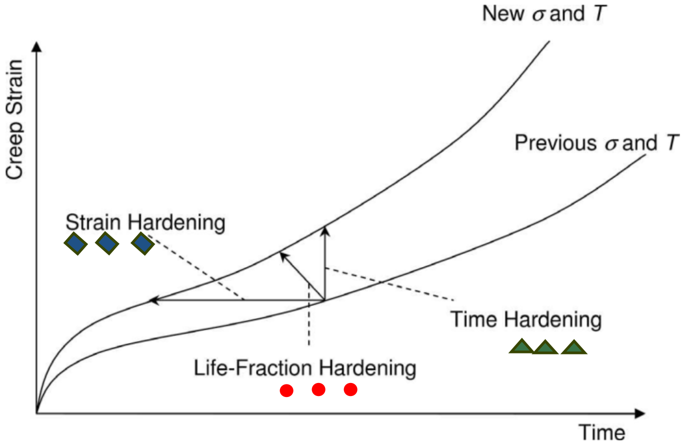
Model developed on a single family Fe+ Pe, Fe+Pe+Ba, Ma+Ba had no higher accuracy than the global model on the whole data set

similar results in
Nakamura et al.
Materials Today Com 2023,
With σy replaced by Hv

Accuracy of
support vector regression (SVR) > random forest (RF) or gradient tree boosting (GTB) methods

Sakurai et al. ISIJ International, Vol. 63 (2023)

Extrapolation ….from these "scalars" toward FE

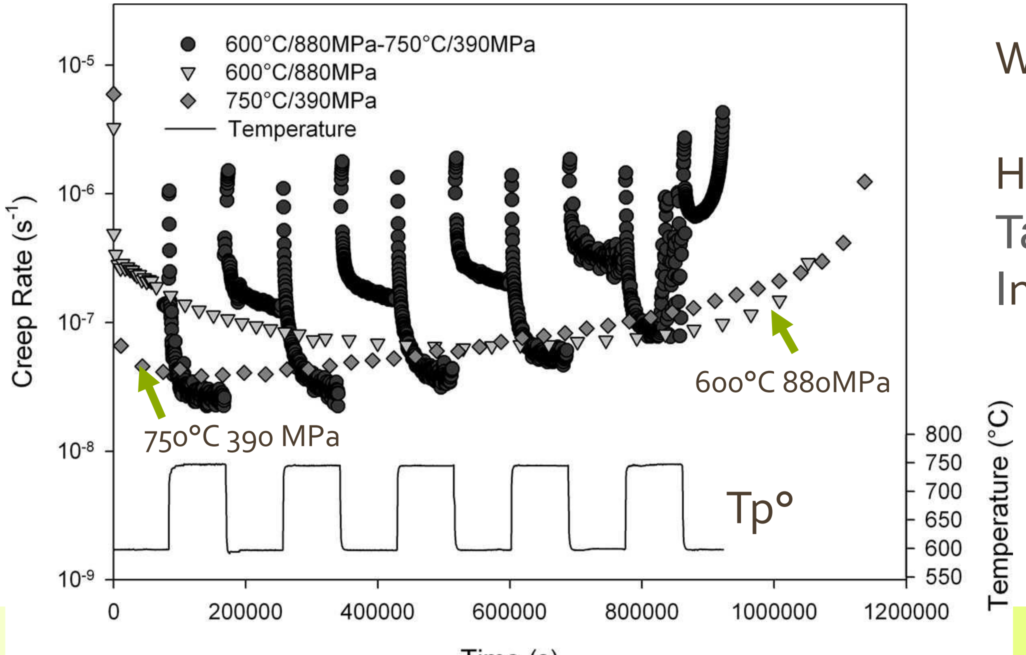


1. Define a **constitutive law** with internal variables

1. Use of them to jump between 1D reference curves $\varepsilon = f(\sigma, T, t)$
(1 curve for σ= cte T=cte)

→ The use of state variables is better than horizontal or vertical shift

Experiments Creep under TP° and stress jump



750°C 390 MPa

600°C 880MPa

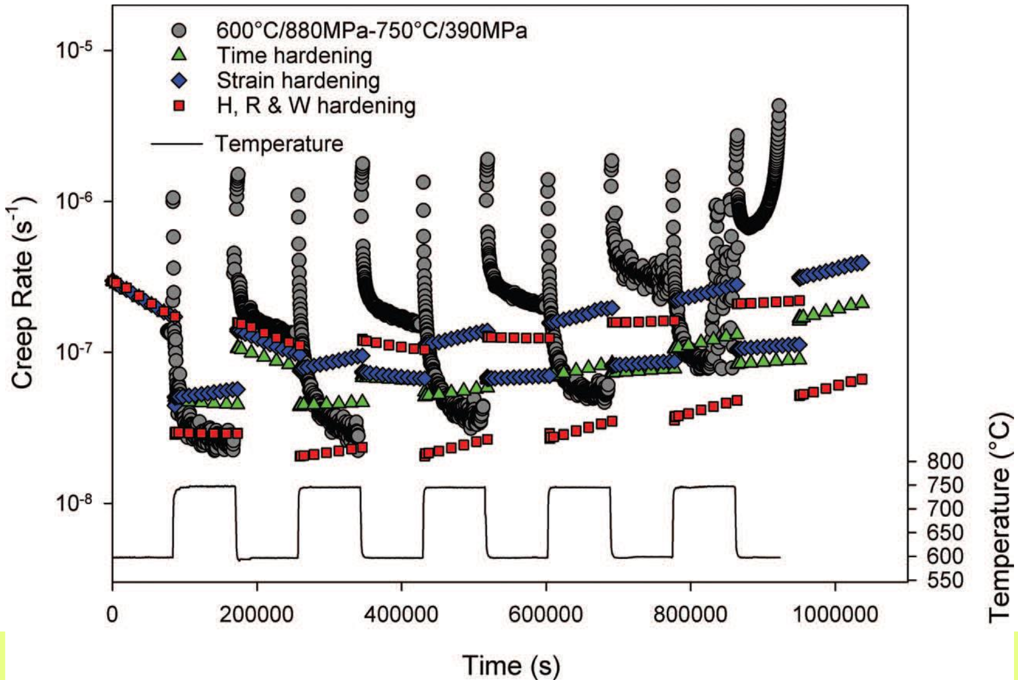
Tp°

Waspaloy

Harrison et al. in Tanski · 2018 IntechOpen

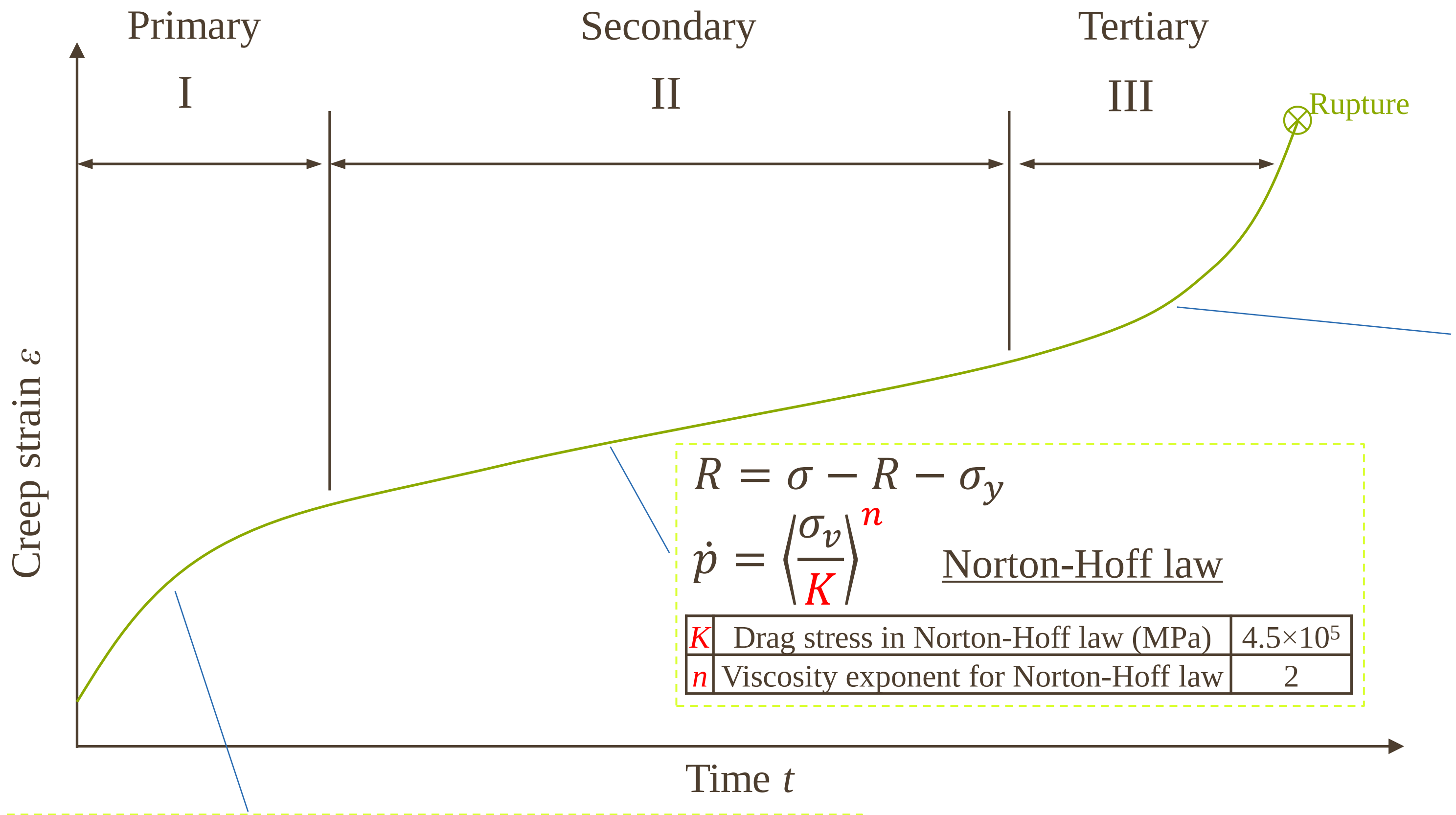
Model predictions still far ..

Model Prediction (Experiment in grey)



Elasto-visco-plastic creep damage model

Helene Morch [Uliege Ph.D. 2022 Walloon Region project], Norton type + damage



$$R = \sigma - R - \sigma_y$$

$$\dot{p} = \left\langle \frac{\sigma_v}{K} \right\rangle^{n}$$ Norton-Hoff law

K	Drag stress in Norton-Hoff law (MPa)	4.5×10^5
n	Viscosity exponent for Norton-Hoff law	2

Isotropic hardening

$$R = Q\left(1 - e^{-b\dot{p}}\right)$$

b	Rate of isotropic hardening	104
Q	Total isotropic saturation size of the yield surface	100

OPTIM
+ Manual identification

Elasticity

T	Temperature (C°)	550
E	Young's modulus (MPa)	1.7×10^5
ν	Poisson's Ratio	0.3

Damage: Rabotnov-Kachanov equation:

$$\dot{D}_c = k_3 \left(\frac{Y\left(\sigma^d * k_4\right)}{S_c} \right)^{s_c} \frac{1}{(1-D)^k}$$

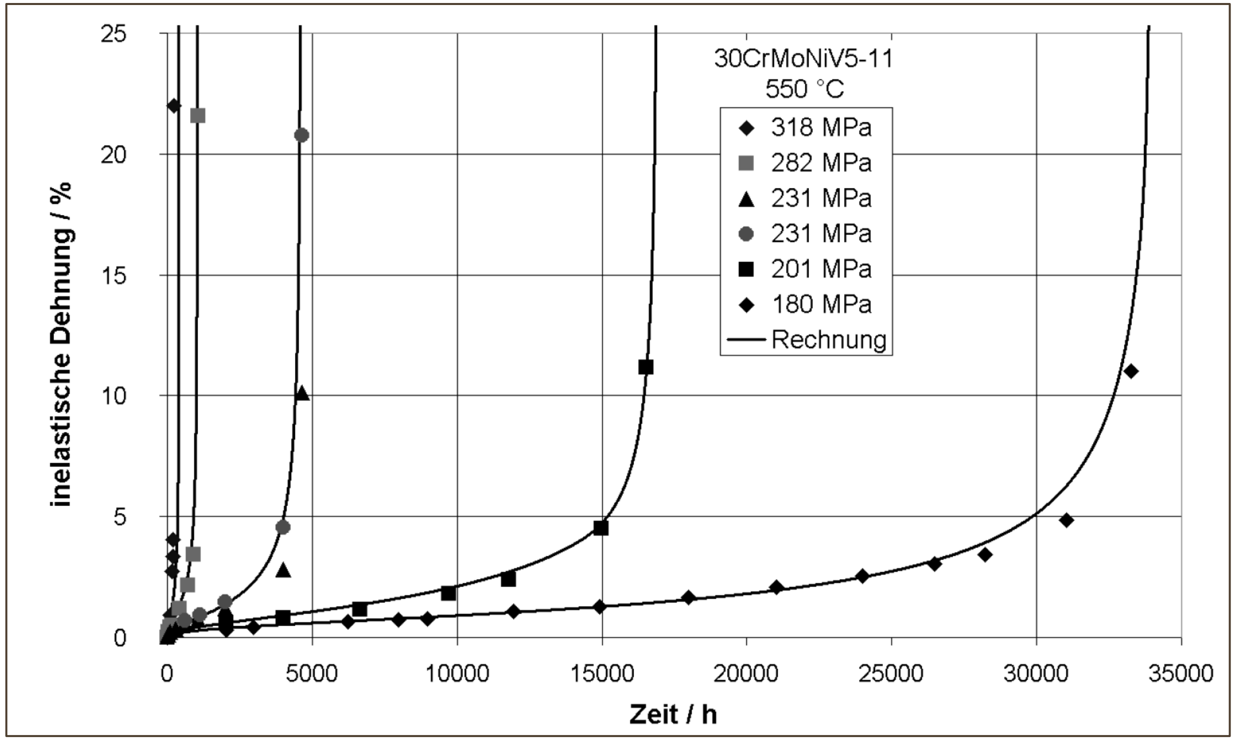
h	Mico-defects closure parameter	0.2
D_{crit}	Critical damage value (<1)	0.99
τ	Specific time for the appearance of creep	1×10^5
k_3	Global safety coefficient on creep damage	1
k_4	Safety coefficient applied to stress level on creep damage	1
S_c	Creep damage parameter	38.00
s_c	Creep damage exponent	3.50
k_c	Kachanov creep damage exponent	4.00

Law identified for 30CrMoNiV5-11

R. Ahmed, et al. Proceedings of the ASME 2012 Pressure Vessels &Piping Conf.2012

Implemented in Lagamine FE code PhD Morch ULiege 2022

Used Creep curves from literature for 30CrMoNiV5-11



Schemmel J. Beschreibung des Verformungs-, 2003.

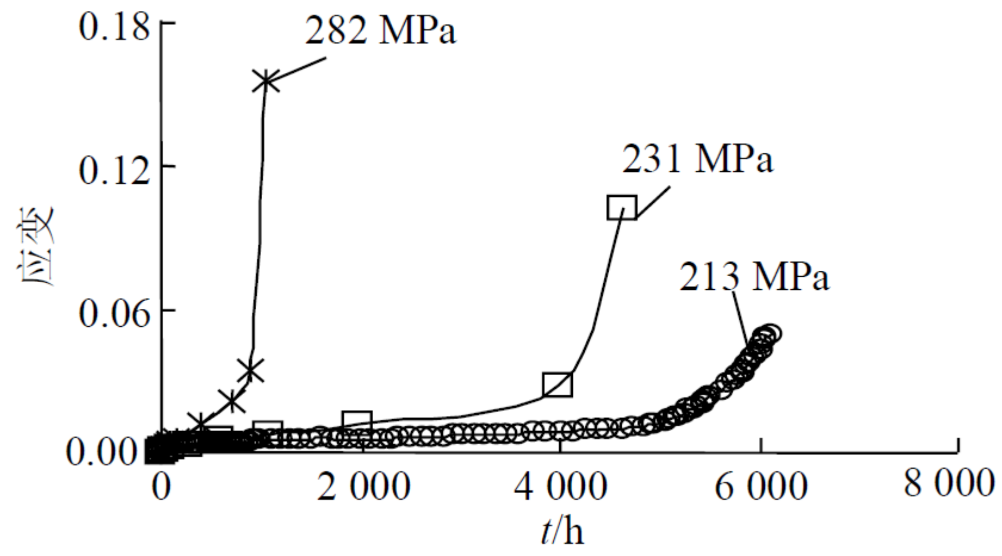
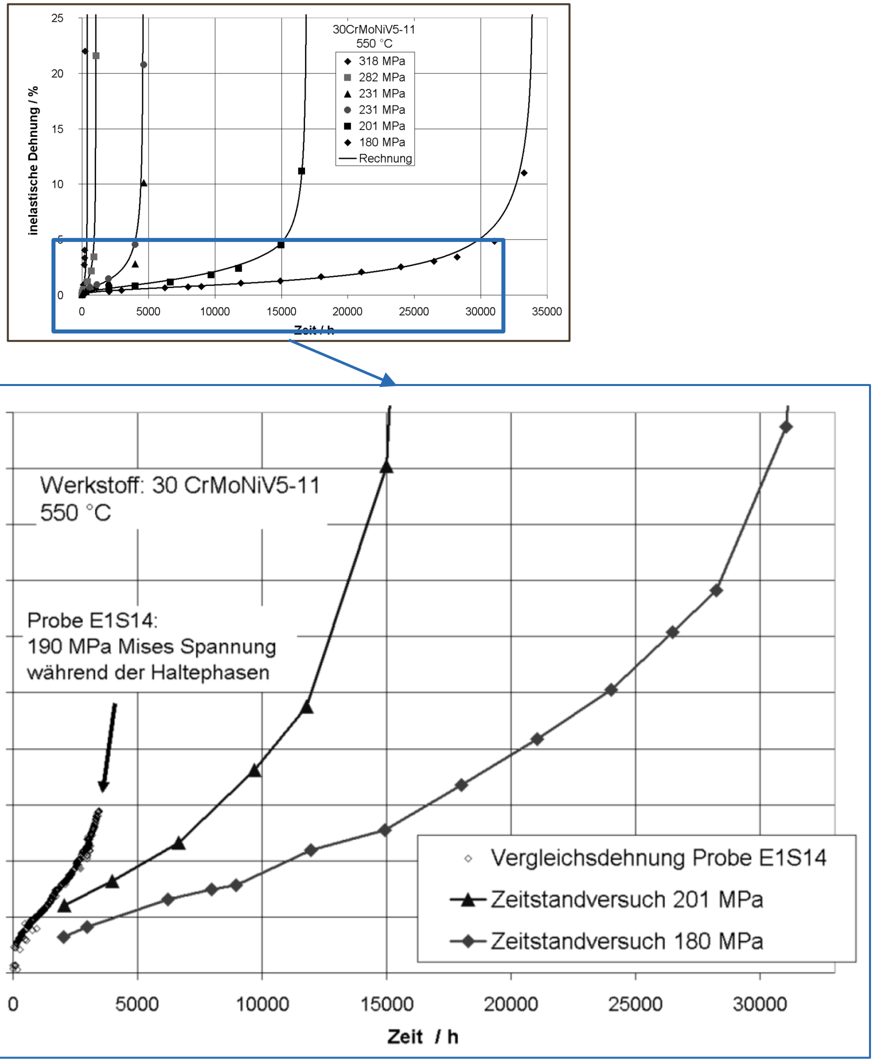


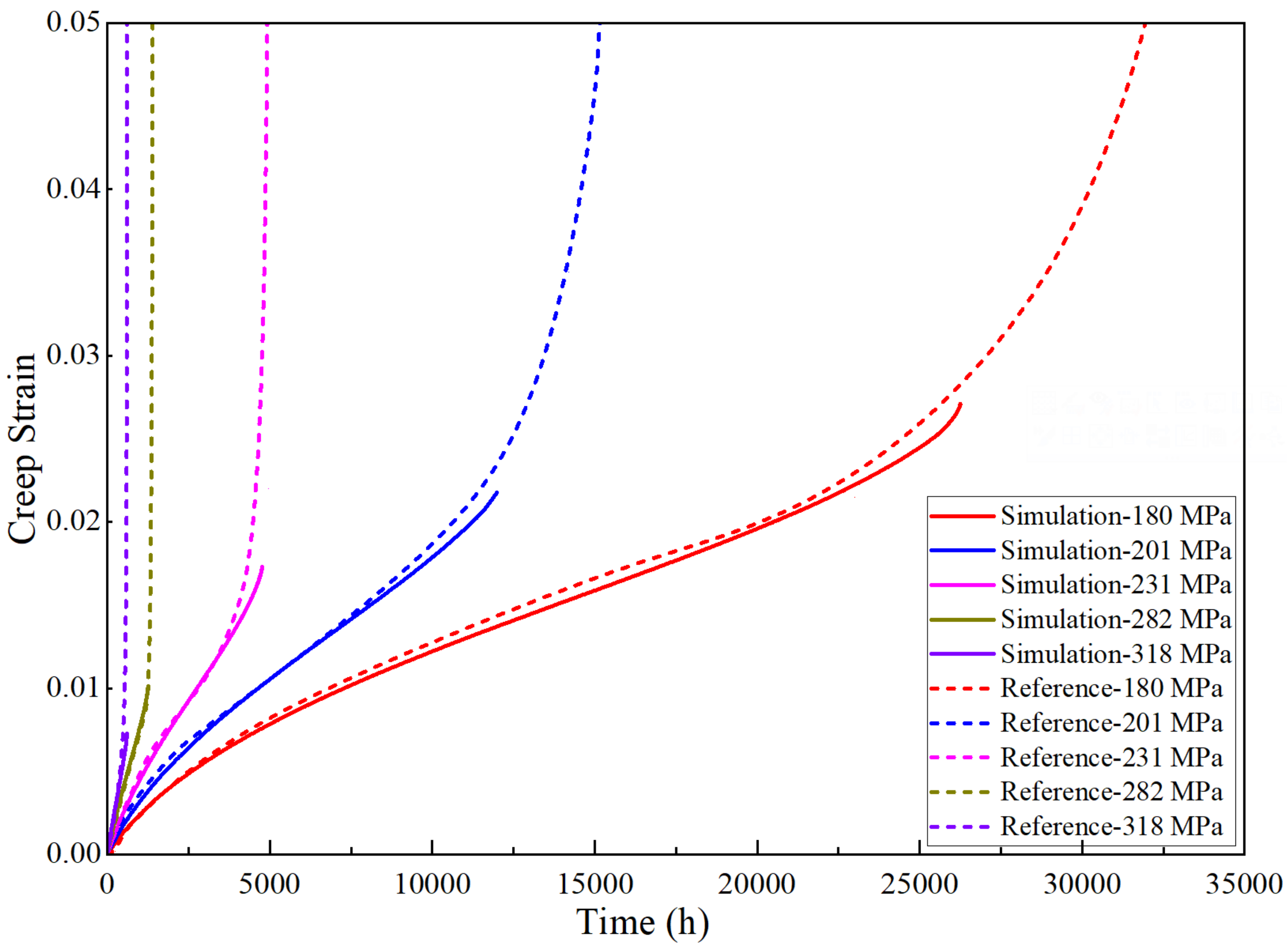
图 5　30CrMoNiV5-11 蠕变数据

Fig. 5　Creep data of 30CrMoNiV5-11

徐鸿,倪永中,王树东. 中国电机工程学报,2009,29(32):88-91.

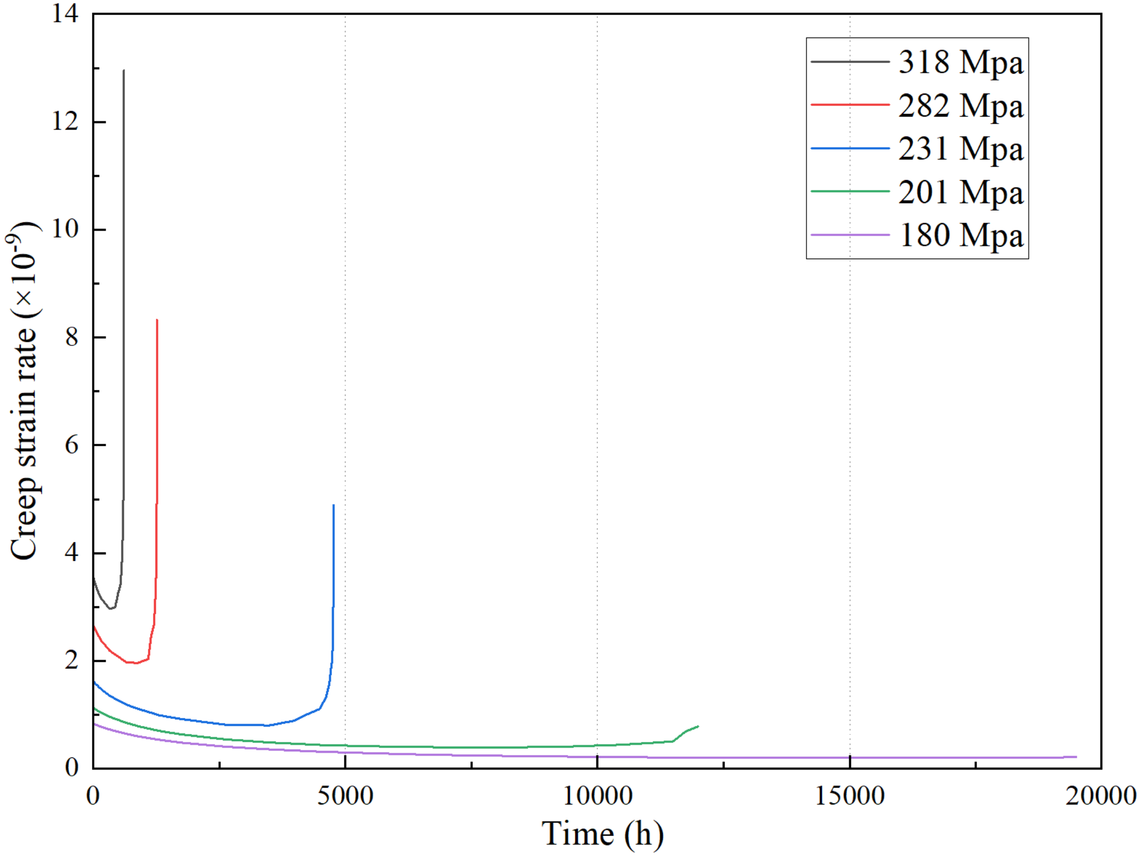
Single element test (performed by ULiege Lagamine)





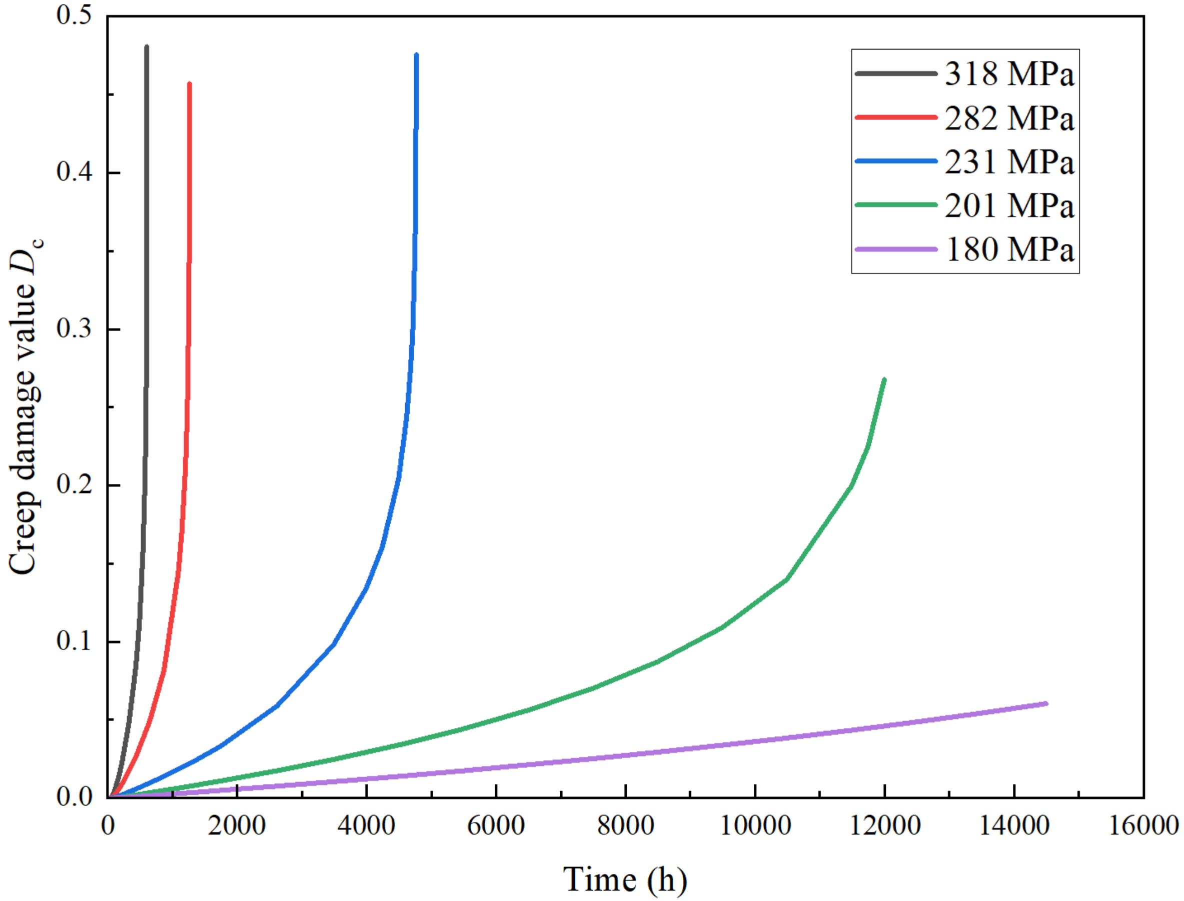
Single element test (Creep strain rate & Damage value-time)

Creep strain rate



(performed by ULiege Lagamine)

Creep damage value



$$\tilde{\sigma} = \frac{\sigma}{1 - hD}$$

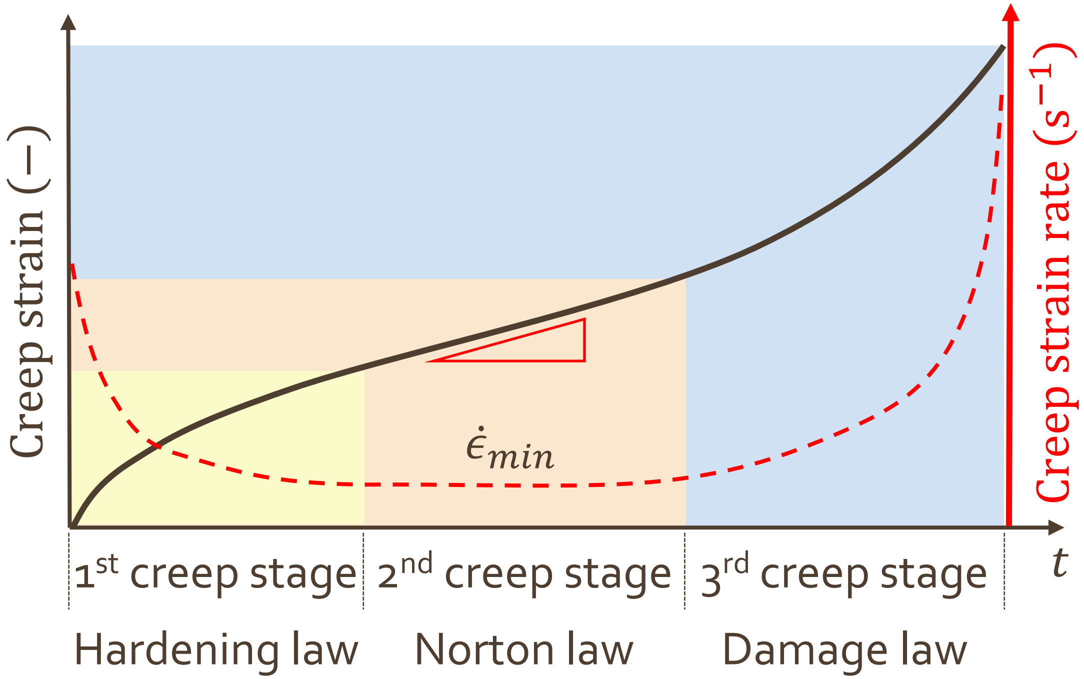
- Microdefects closure h
- Creep damage D

Creep modeling issues with Norton type law

Norton viscosity function

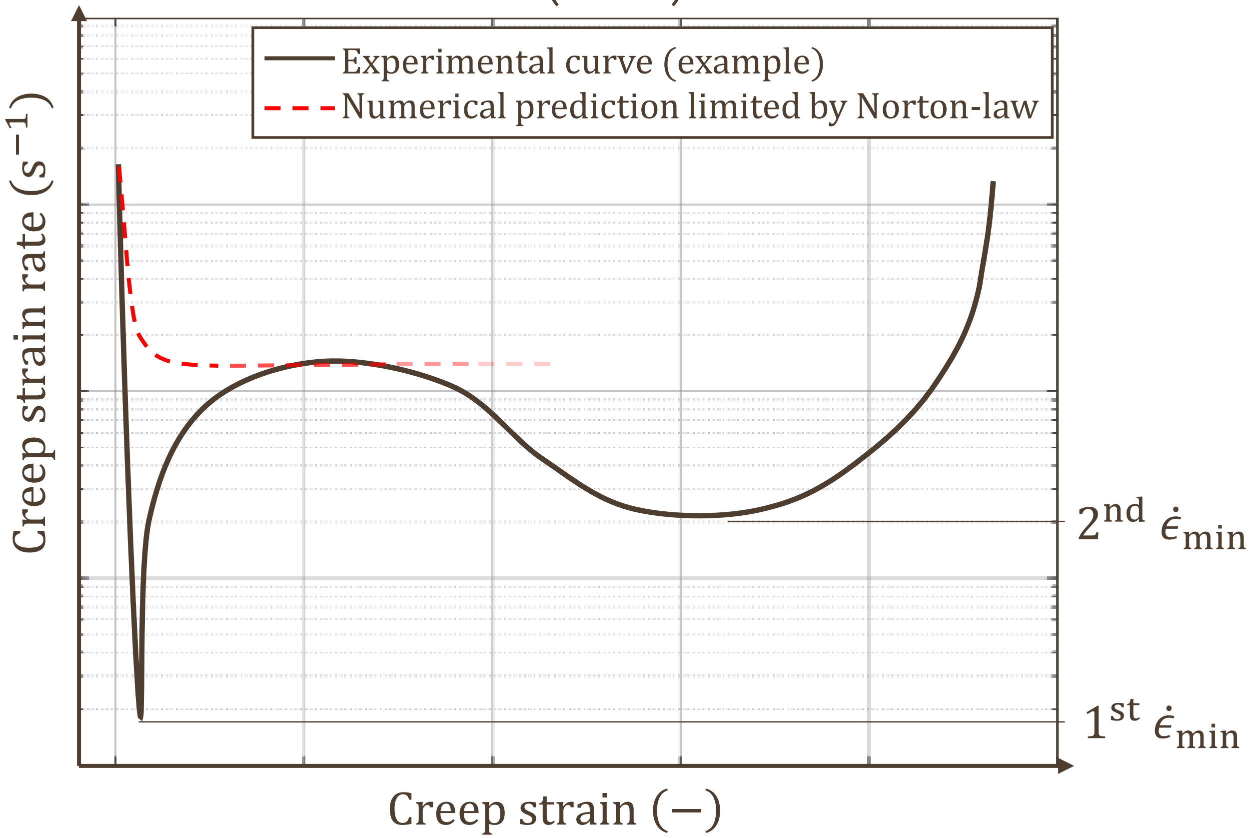
$$\dot{p} = \left\langle \frac{\sigma_v}{K} \right\rangle^{n}$$

OK for classic creep behavior:



~~OK~~ for materials with non-classical creep

Non-classical creep response: 2-step creep rate minima (800H)



*: Experimental curves after (V. Gutmann & R. Bürgel, 1983)

Graham-Walles viscosity function

→ higher flexibility

Non-conventional approach, addition of i functions, implemented in Lagamine FE code

$$\dot{\epsilon}^p = \sum_{i=1}^{vp_i} K_i \exp\left(\frac{\mathrm{T}}{C}\right) [\overline{\sigma}]^{n_i} (\epsilon^p)^{m_i}$$

→ $f(\overline{\sigma}, \mathrm{T}, \epsilon^p)$

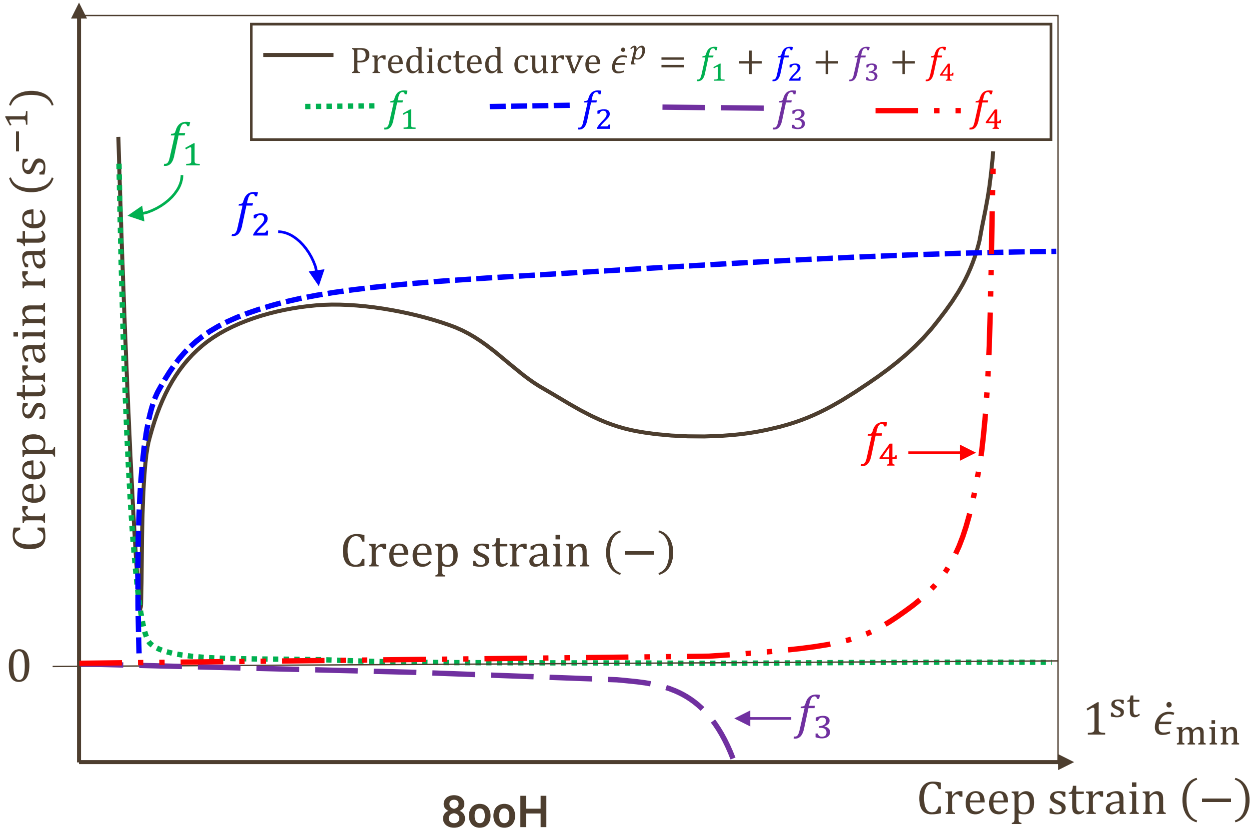
$\overline{\sigma}$	Eq. stress	(MPa)
T	Temperature	(ºC)
ϵ^p	Eq. plastic strain	(−)

→ non-linear!

→ Parameters:

C (ºC)	1
	+
$K_i\,(\mathrm{s}^{-1})$ $n_i\,(-)$ $m\,(-)$	3 per equation (vp_i)

Possible to model non-classical creep response:
2-step creep rate minima



On going PhD C. Rojas ULiege, ACOMEN 2022

Graham-Walles viscosity function

$$\dot{\epsilon}^p = \sum_{i=1}^{vp_i} \boxed{K_i} \exp\left(\frac{\mathrm{T}}{\boxed{C}}\right)(\bar{\sigma})^{\boxed{n_i}}(\epsilon^p)^{\boxed{m_i}}$$

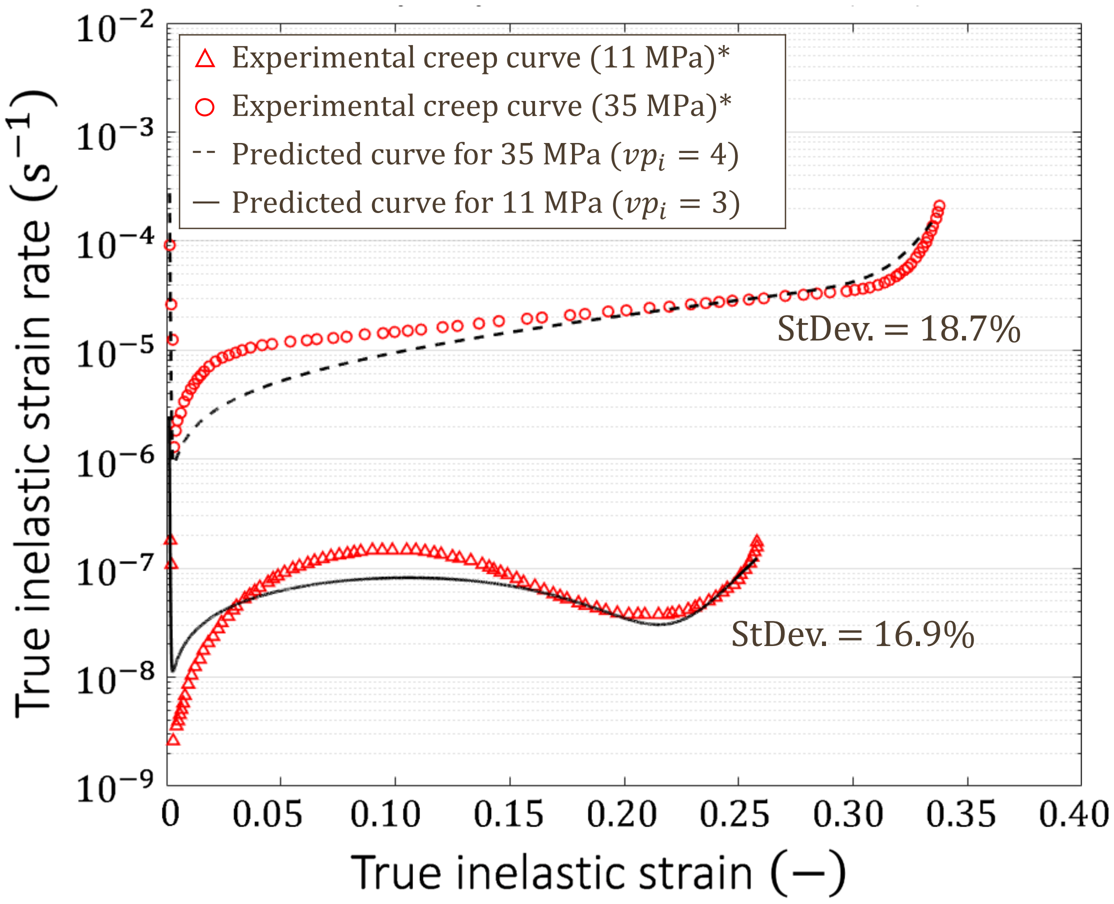
$\rightarrow f(\bar{\sigma}, \mathrm{T}, \epsilon^p)$

$\bar{\sigma}$	Eq. stress	(MPa)
T	Temperature	(ºC)
ϵ^p	Eq. plastic strain	$(-)$ → non-linear!

$\rightarrow$ Parameters:

C	(ºC)	1
		+
K_i	(s^{-1})	3 per equation (vp_i)
n_i	$(-)$	
m_i	$(-)$	

Case study: creep response of 800H alloy at 1000°C



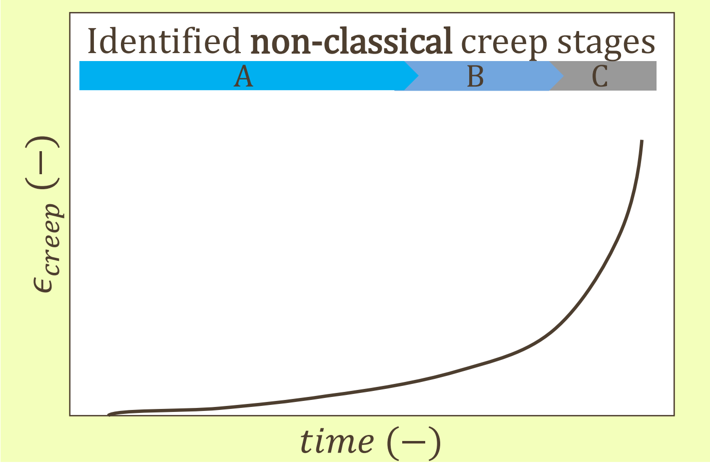
*: Experimental curves after (V. Gutmann & R. Bürgel, 1983)

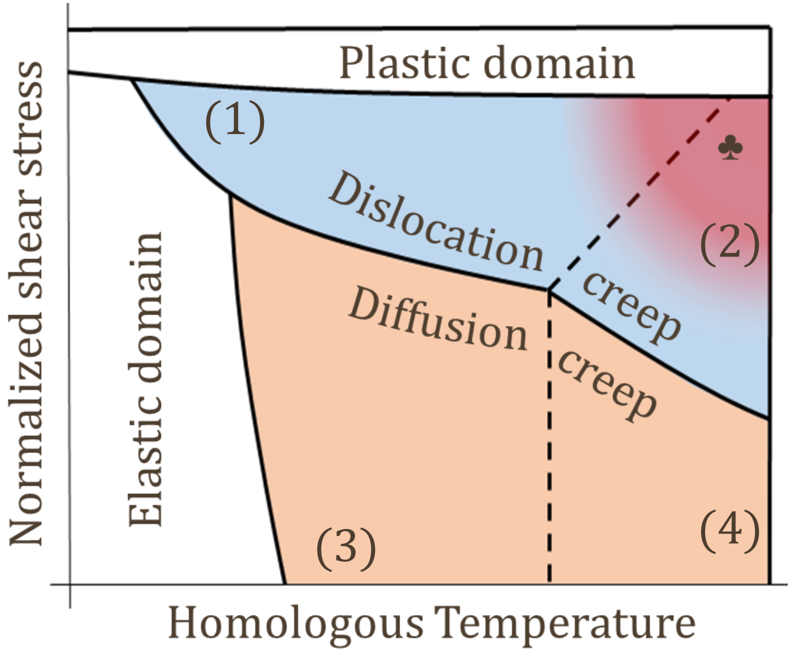
Contents

Creep mechanisms

Classical curve (low microstructure evolution)

Creep strain v/s time

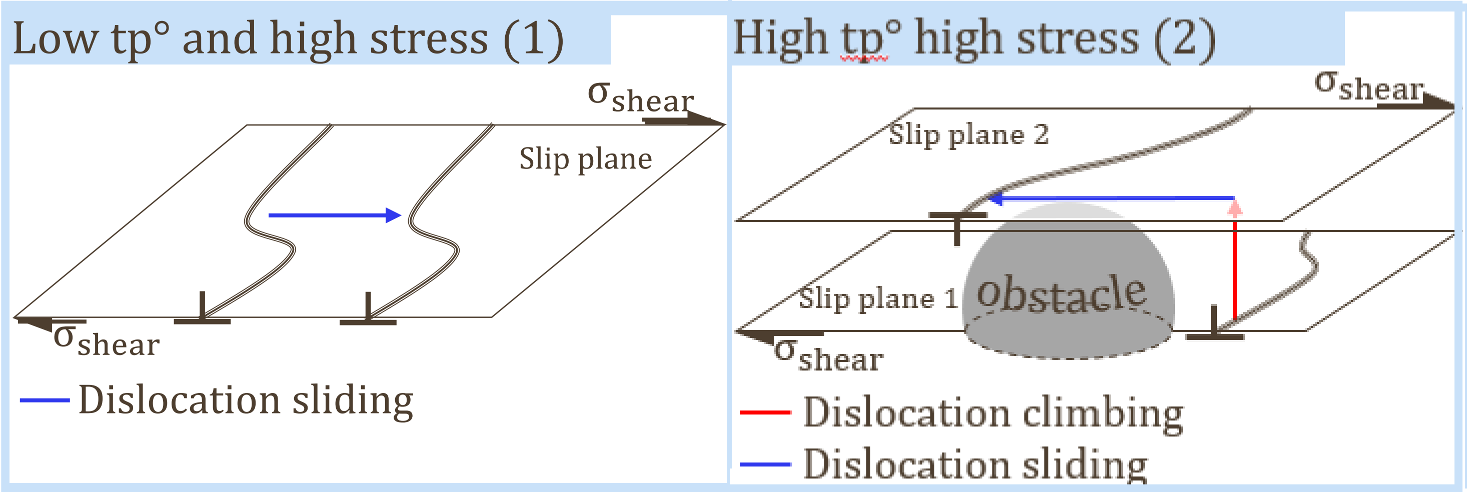




♣: Dynamic recrystallization (DRX)

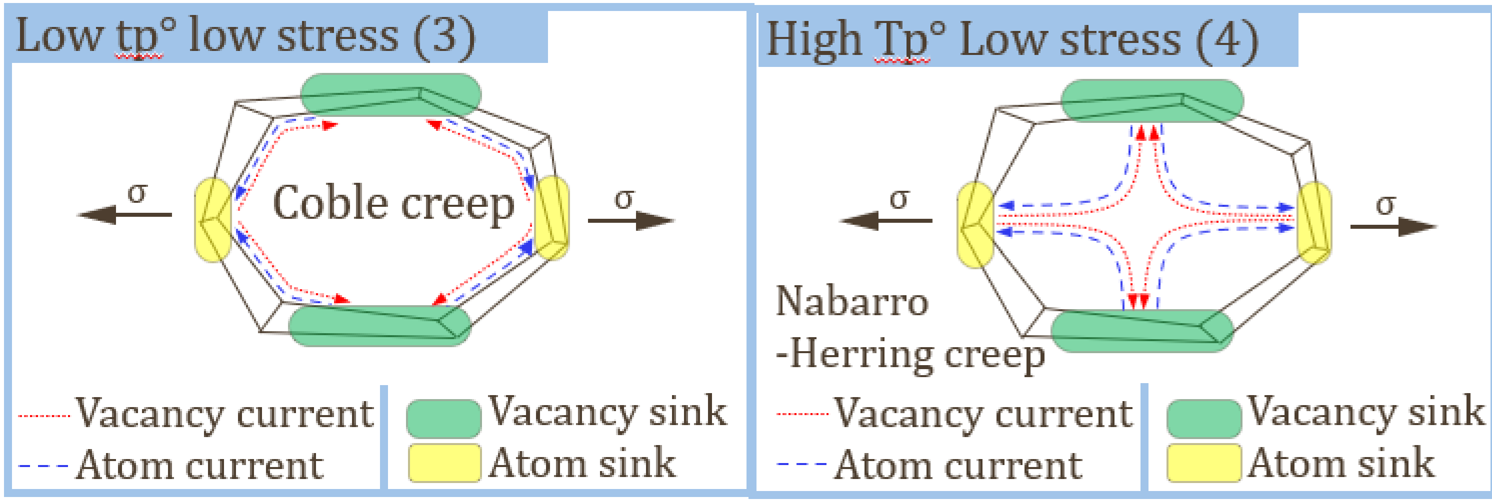
Time effect

Dislocation-driven creep



Dislocation glide, shearing or looping around obstacles, are freed by vacancy diffusion → generation intra granular deformation

Diffusion-driven creep

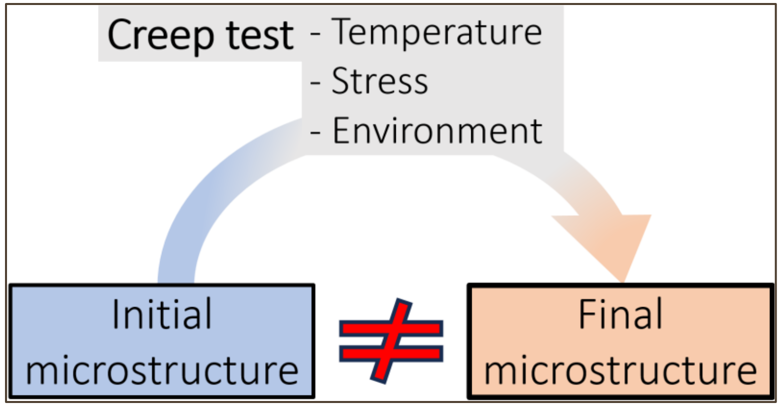


Diffusion : along GB inside the grain → GB sliding

Semi-physical creep model → macro FE Coupled approach ?

Creep properties of materials depend on:

- **Permanent** microstructural features
- **Evolving** microstructural features



Creep test - Temperature

- Stress

- Environment

Initial microstructure ≠ Final microstructure

Accurate creep modeling requires microstructure evolution
Orowan equation to link macro strain and microstructure

$$\dot{\epsilon} = \frac{\rho b v_g}{M}$$

$\dot{\epsilon}$	Creep rate	(s^{-1})
ρ	Dislocation density	(m^{-2})
b	Burger's vector	(m)
v_g	Dislocation glide velocity	(ms^{-1})
M	Taylor factor	$(-)$

(S. Mesarovic et al., Springer, 2019)

	Semi-physical	Phenomenological
• Deterministic	• Statistical	• Empirical
• Nano-scale	• Meso-scale	• Macro-scale
• Complex	• Moderate	• Simplified

A Macro law (used in macro FE simulations)

$T, \dot{T}$, σ or ε loading, q state variables

→ $\dot{\varepsilon}$ or $\dot{\sigma}$, *updated* q state variables

→ Macro law identified through predicted creep curves computed by a creep Meso-scale model

OR

→ Macro law sequentially or continuously updated based on state variable(s) kinetic of reflecting microstructure state computed

-from a set of equations

-from interpolation within in a data base

-from a meso or nano model (phase-field…)

OR

-multi scale …

Semi-physical creep modeling approach

N.M. Ghoniem et al., 1990 → a comprehensive mean-field model

5 co-dependent non-linear equations.
Each = specific microstructural feature involved in the creep mechanism.

$\dot{\epsilon} = \frac{\rho_m b v_g}{M}$	Creep strain rate
$\dot{\rho}_m = v_g \left[\rho_m^{3/2} + \frac{\beta \rho_s R_{sb}}{h_b^2} - \frac{\rho_m}{2R_{sb}} - \delta_a(\rho_m^2 - \rho_m \rho_s)\right] - 8\rho_m^{3/2} v_{cm}$	Mobile dislocation density
$\dot{\rho}_s = v_g \left[\frac{\rho_m}{2R_{sb}} - \delta_a \rho_m \rho_s\right] - 8\frac{\rho_s}{h_b} v_c$	Static (dipole) dislocation density
$\dot{\rho}_b = 8(1 - 2\zeta)\frac{\rho_s}{h_b} v_c - \frac{\rho_b}{R_{sb}} M_{sb} \left[P_{sb} - 2\pi \left(\sum_i {r_p^2}_i \cdot N_{p_i}\right) \gamma_{sb}\right]$	Boundary dislocation density
$\dot{R}_{sb} = M_{sb} \left[P_{sb} - 2\pi \left(\sum_i {r_p^2}_i \cdot N_{p_i}\right) \gamma_{sb}\right] - \mu \eta_v K_c R_{sb} \left[(\rho_m + \rho_s)^{1/2} - \frac{K_c}{2R_{sb}}\right] \frac{\Omega D_s}{KT}$	Subgrain radius

N.M. Ghoniem et al., 1990 Res Mechanica

Semi-physical creep modeling approach

N.M. Ghoniem et al., 1990 → a comprehensive mean-field model

5 co-dependent non-linear equations.
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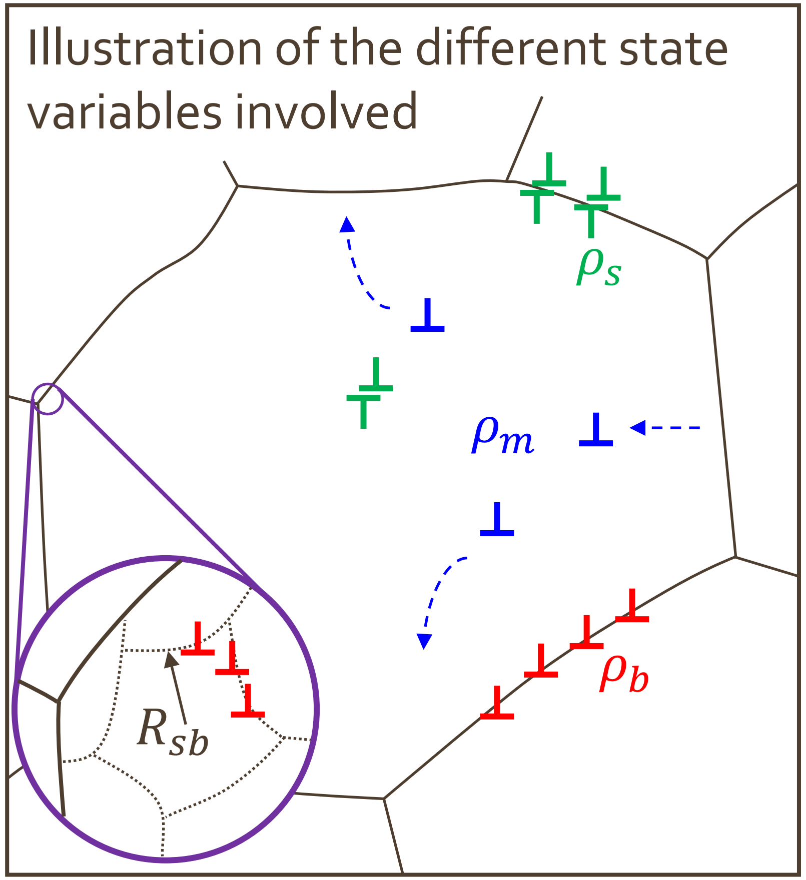
Illustration of the different state variables involved

C. Rojas ULiege

N.M. Ghoniem et al., 1990 Res Mechanica

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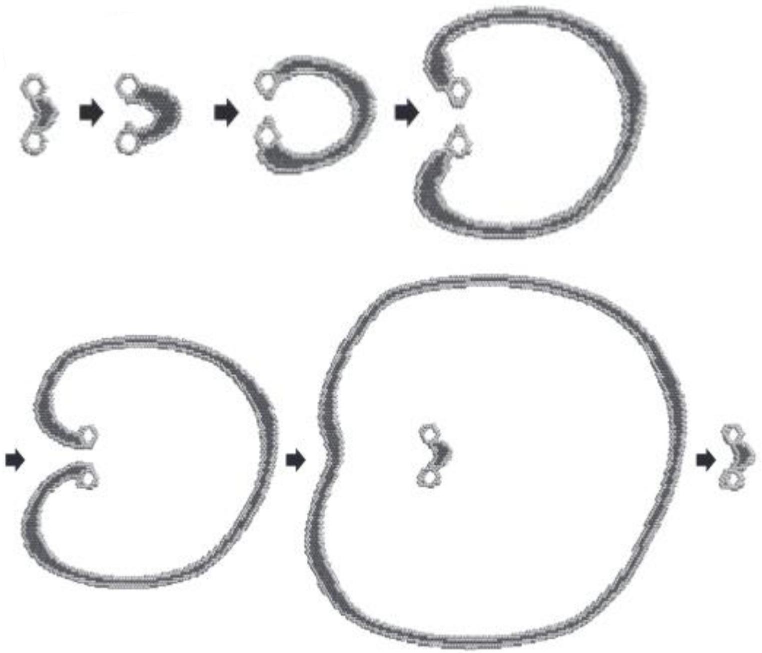
Frank-Read dislocation source



(T. Shimokawa & S. Kitada, 2014)

N.M. Ghoniem et al., 1990 Res Mechanica

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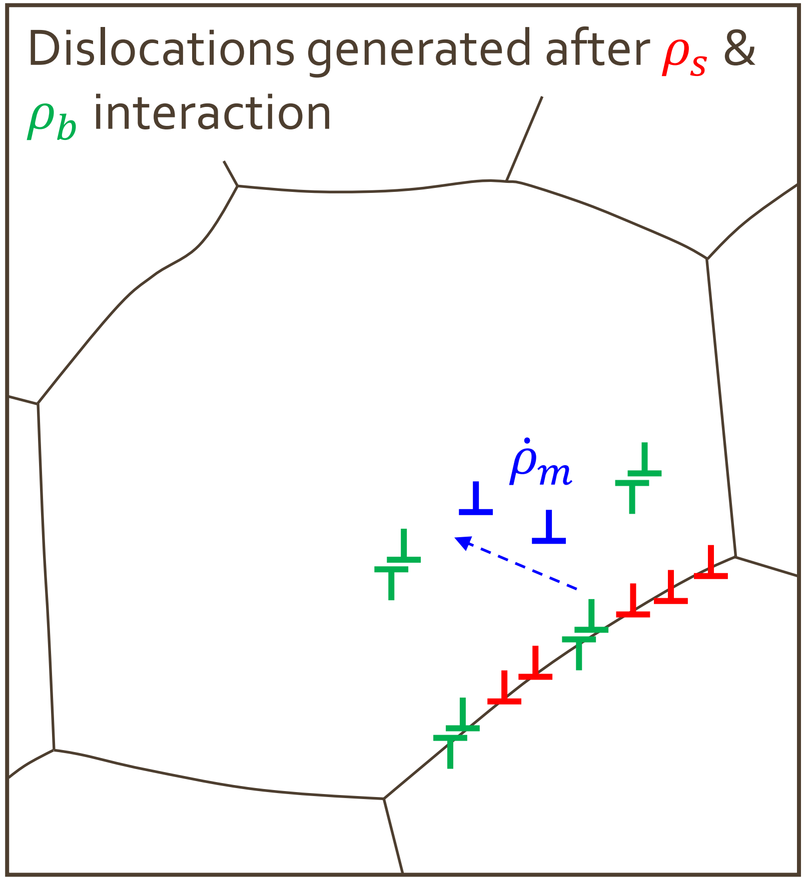
Dislocations generated after ρ_s & ρ_b interaction

C. Rojas ULiege

N.M. Ghoniem et al., 1990 Res Mechanica

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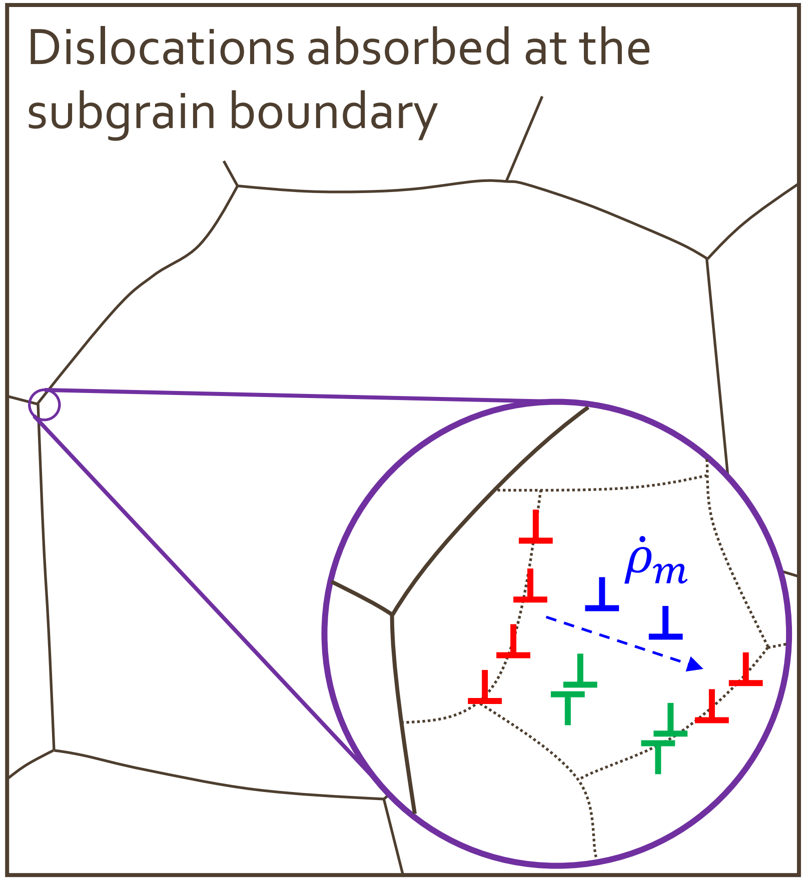

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$$\dot{\rho}_s = v_g \left[\frac{\rho_m}{2R_{sb}} - \overset{B}{\boxed{\delta_a \rho_m \rho_s}} \right] - 8\frac{\rho_s}{h_b} v_c$$

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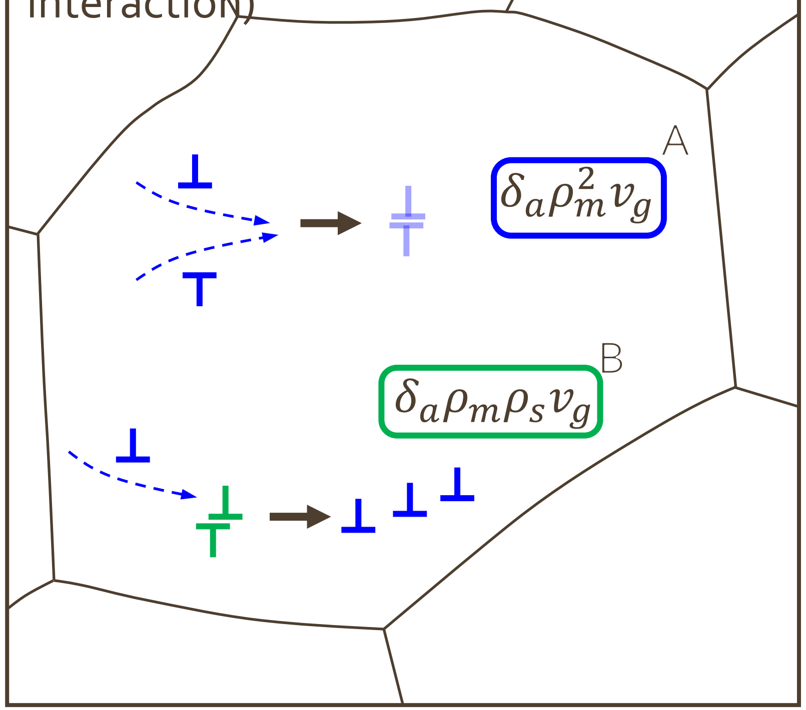
Dynamic recovery: Annihilation by **glide** (ρ_m-ρ_m and ρ_m-ρ_s interaction)



C. Rojas ULiege

N.M. Ghoniem et al., 1990 Res Mechanica

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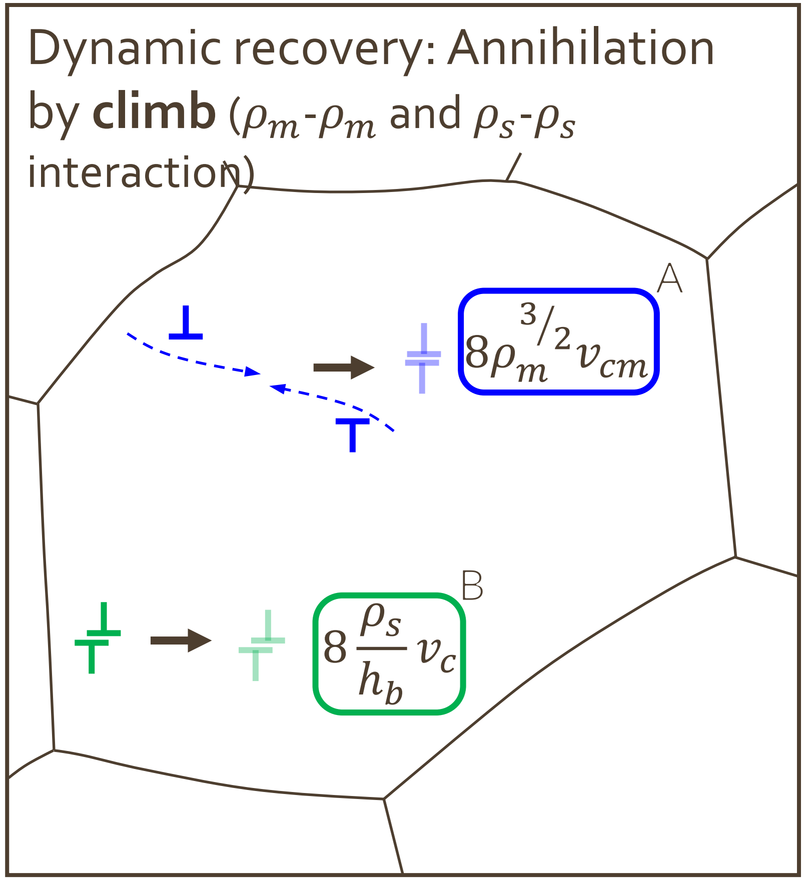

Dynamic recovery: Annihilation by **climb** (ρ_m-ρ_m and ρ_s-ρ_s interaction)

C. Rojas ULiege

N.M. Ghoniem et al., 1990 Res Mechanica

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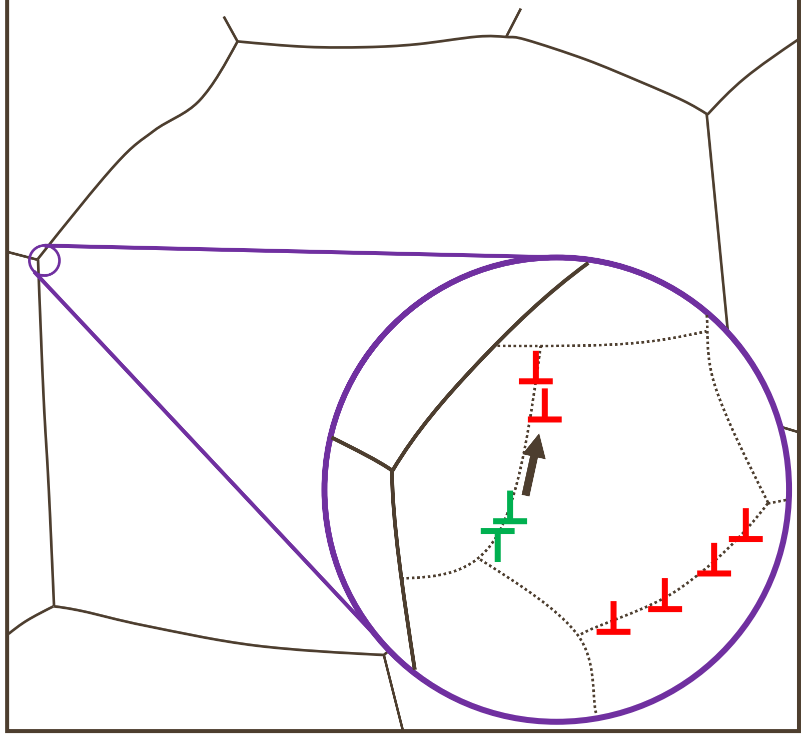
Share of boundary dislocations produced after ρ_s



C. Rojas ULiege

N.M. Ghoniem et al., 1990 Res Mechanica

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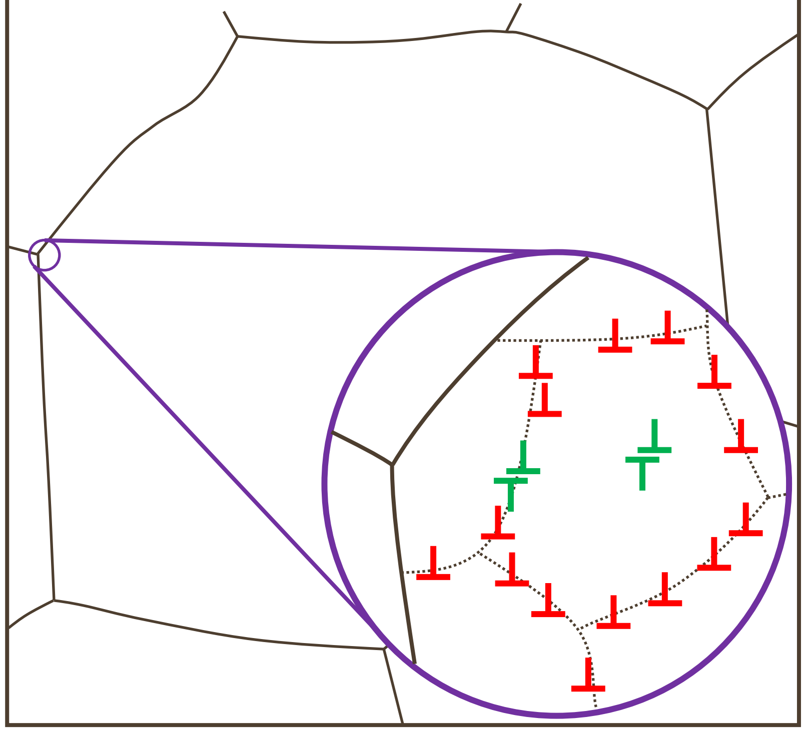
$$\dot{R}_{sb} = \underbrace{M_{sb}\left[P_{sb} - 2\pi\left(\sum_i r_{p\ i}^2 \cdot N_{p_i}\right)\gamma_{sb}\right]}_{\text{Subgrain growth}} - \underbrace{\mu \eta_v K_c R_{sb}\left[(\rho_m + \rho_s)^{1/2} - \frac{K_c}{2R_{sb}}\right]\frac{\Omega D_s}{KT}}_{\text{Subgrain nucleation}}$$

Evolution of subgrains: growth and nucleation terms



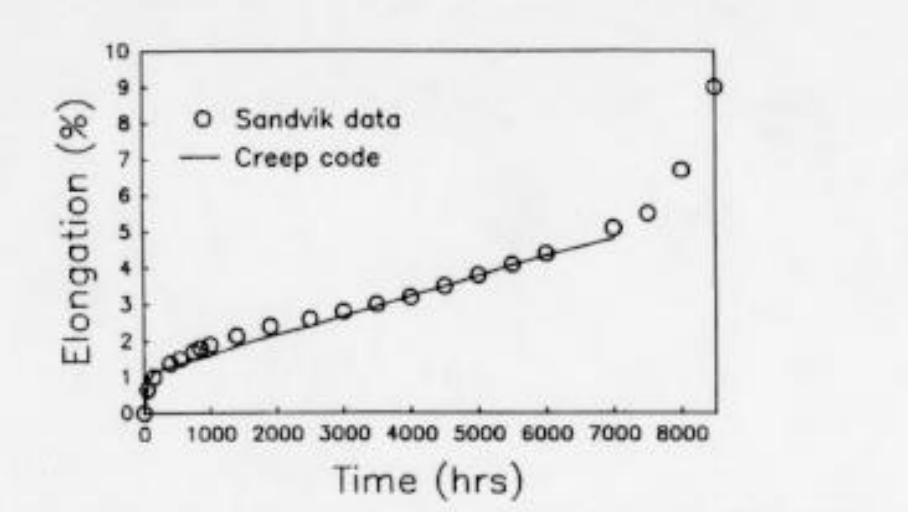
C. Rojas ULiege

N.M. Ghoniem et al., 1990 Res Mechanica

Martensitic steel HT9 - Ghoniem model application

Creep curve predictions : validated

- Earlier stade I → II transition point if T ↗
- $\dot{\epsilon}_m \propto \sigma^5$ (steel type forming dislocation cells)
- T ↗ → $\dot{\epsilon}$ ↗ (recovery and glide velocity ↗)
- ρ ↗ with $\dot{\epsilon}$ until saturation



Elongation as a function of time for HT-9 at 550 °C and 227 MPa.

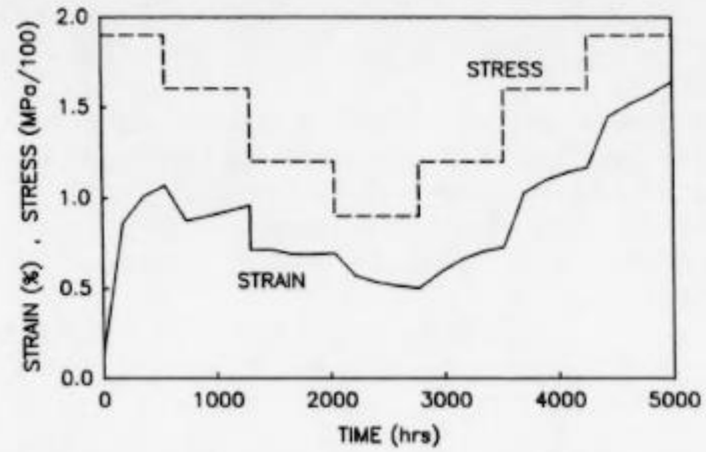
Strain related to stress history is logic

1st stress ↘ $\dot{\epsilon}$ ↘ than ↗

Effective stress applied on dislocation ↘ $\dot{\epsilon}$ ↘

ρ, internal stress readjust, threshold is again reached $\dot{\epsilon}$ ↗

A dislocation model for creep in engineering materials 217



. Time-dependence of accumulated strain for a variable stress history for HT-9 at 550 °C.

N.M. Ghoniem et al., 1990 Res Mechanica

Semi-physical creep modeling approach

Accommodation of more particles (MX and $M_{23}C_6$) phase effects,
New functions for Cavitation damage (D_{cav}) **and** precipitate coarsening (D_{ppt})

$$\dot{\epsilon} = \frac{\rho_m b v_g}{M\left(1 - D_{ppt}\right)\left(1 - D_{cav}\right)}$$

$$\dot{\rho}_m = v_g\left[\rho_m^{3/2} + \frac{\beta\rho_s R_{sb}}{h_b^2} - \frac{\rho_m}{2R_{sb}} - \delta_a(\rho_m^2 - \rho_m\rho_s)\right] - 8\rho_m^{3/2} v_{cm}$$

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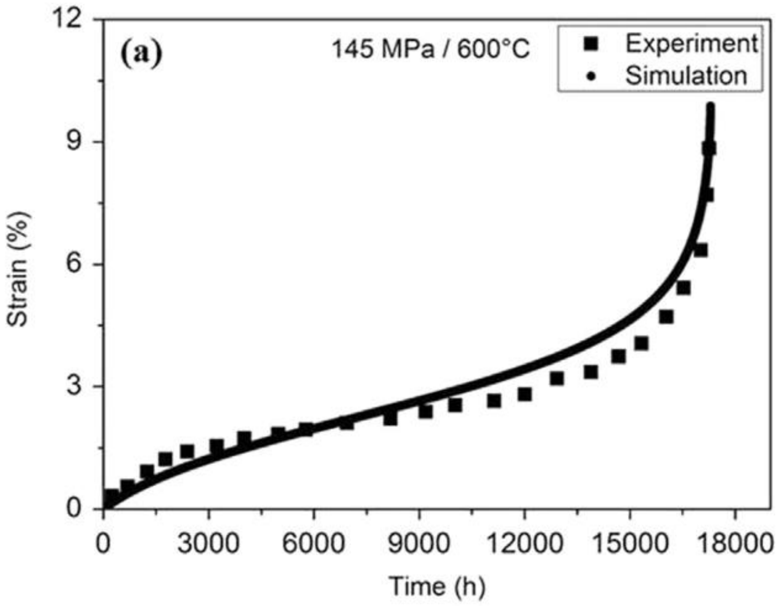
$$\dot{R}_{sb} = M_{sb}\left[P_{sb} - 2\pi\left(\sum_i r_{p\,i}^2 \cdot N_{p_i}\right)\gamma_{sb}\right] \cancel{- \mu\eta_v K_c R_{sb}\left[(\rho_m + \rho_s)^{1/2} - \frac{K_c}{2R_{sb}}\right]\frac{\Omega D_s}{KT}}$$

Application on P92 tempered martensitic steel



(S.D. Yadav et al., 2016)

S.D. Yadav et al., MSEA 2016

Semi-physical creep modeling approach

Addition of effective velocity (v_{eff}) calculated as the sum of glide + climb velocity contributions

$$\dot{\epsilon} = \frac{\rho_m b v_{eff}}{M\left(1 - D_{ppt}\right)\left(1 - D_{cav}\right)}$$

$$\dot{\rho}_m = v_g \left[\rho_m^{3/2} + \frac{\beta \rho_s R_{sb}}{h_b^2} - \frac{\rho_m}{2R_{sb}} - \delta_a\left(\rho_m^2 - \rho_m \rho_s\right) \right] - 8\rho_m^{3/2} v_{cm}$$

$$\dot{\rho}_s = v_g \left[\frac{\rho_m}{2R_{sb}} - \delta_a \rho_m \rho_s \right] - 8\frac{\rho_s}{h_b} v_c$$

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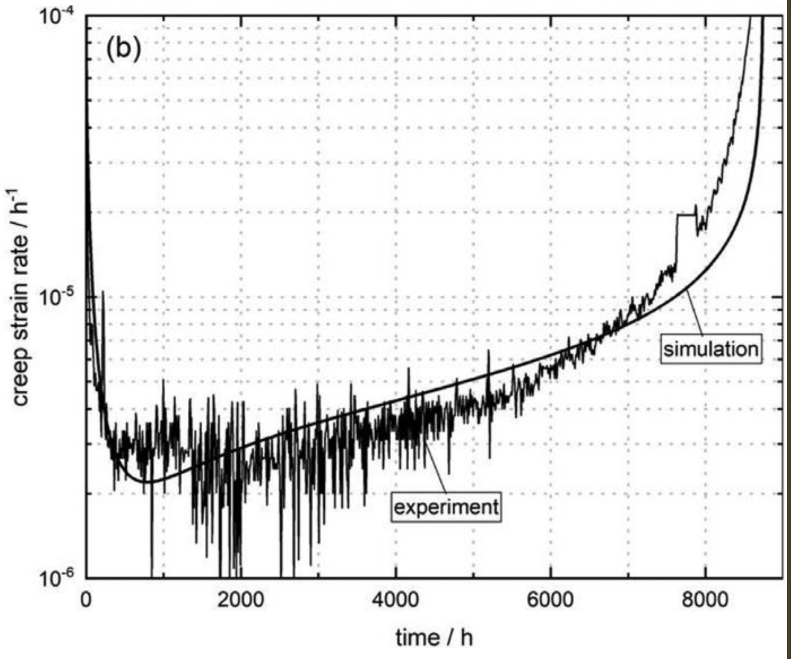
Application on P91 austenitic-martensitic steel



(F. Riedlsperger et al., 2020)

F. Riedlsperger et al., Materialia 2020

Semi-physical creep modeling approach

The base model is modified to include more complex intragranular precipitate-dislocation interaction terms, and a **diffusional creep rate term**

$$\dot{\epsilon}_{diff} = A_c \frac{D_{gb}\delta_{gb}\sigma_{app}\Omega}{8R_{sb}^3 K_B T}$$

$$\dot{\epsilon}_{disl} = \frac{\rho_m b v_g}{M(1-D_{cav})}$$

$$\dot{\rho}_m = v_g\left[\rho_m^{3/2} + \frac{\beta\rho_s R_{sb}}{h_b^2} - \frac{\rho_m}{2R_{sb}} - \delta_a(\rho_m^2-\rho_m\rho_s)\right] - 8\rho_m^{3/2} v_{cm}$$

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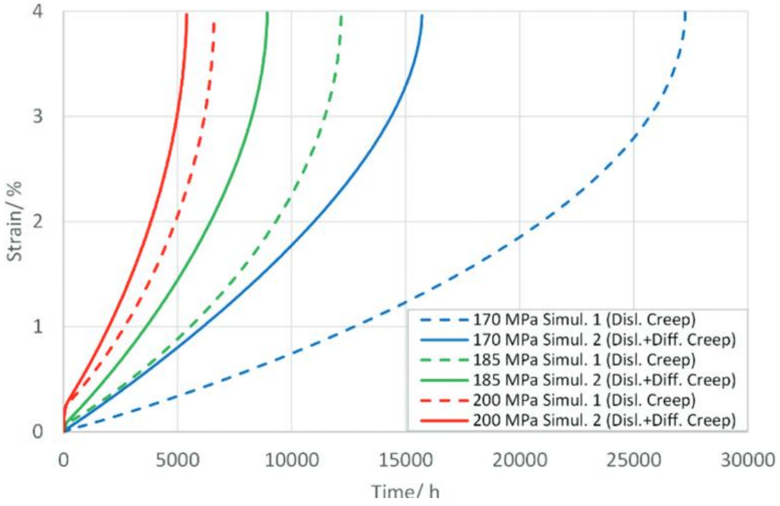
$$\cancel{\dot{R}_{sb} = M_{sb}\left[P_{sb}-2\pi\left(\sum_i r_{p\,i}^2\cdot N_{p\,i}\right)\gamma_{sb}\right] - \mu\eta_v K_c^2\left[(\rho_m+\rho_s)^{1/2} - \frac{K_c}{2R_{sb}}\right]\frac{\Omega D_s}{2KT}}$$

Application on A617 Ni-based alloy



(F. Riedlsperger et al., 2023)

Semi-physical creep modeling approach

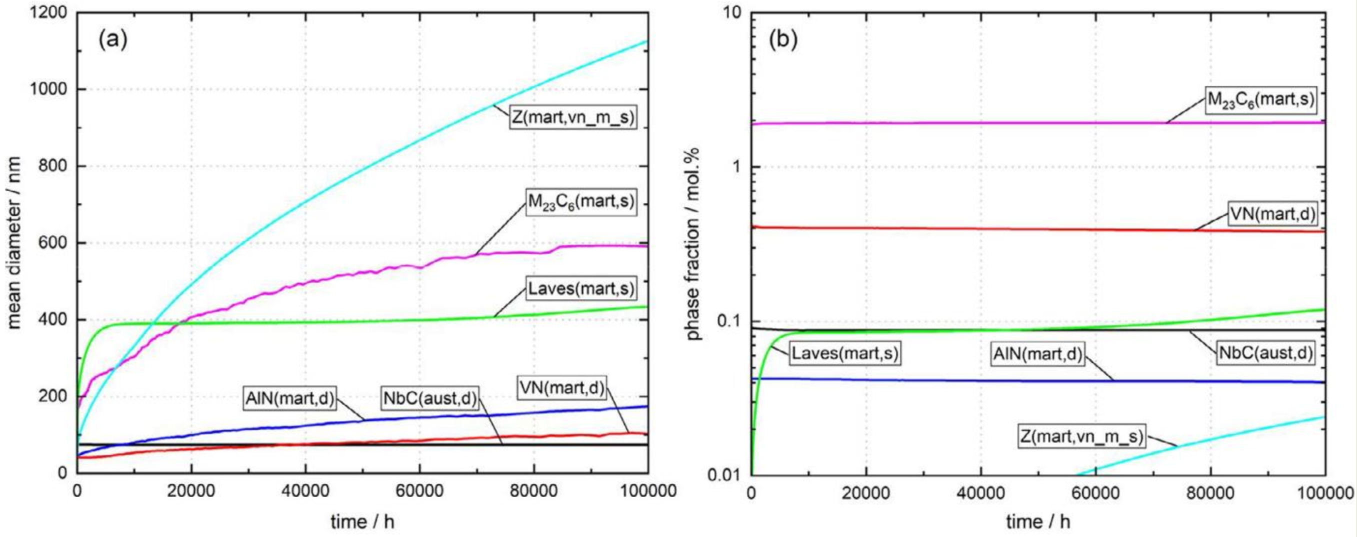
Knowledge on the microstructure evolution is mandatory

- Thermodynamic simulations
- Microstructure characterization after (interrupted) tests

to validate **precipitate state and kinetic**

• Phase fraction	$(\mathrm{mol.\,\%})$
• Mean diameter	(m)
• Nucleation site	(dislocation paths, intra- or interganular,…)?

MatCalc simulations performed for P91 steel



after (F. Riedlsperger et al., 2020)

microstructure evolution by 4 physical variables:

ρ_m	Mobile dislocation density	(m^{-2})
ρ_s	Static dislocation density	(m^{-2})
ρ_b	Dynamic dislocation density	(m^{-2})
R_{sgb}	Sub-grain radius	(m)

creep behavior ($\dot{\epsilon}$) is conditioned by their:

- Growth
- Production
- Annihilation
- Transformation

F. Riedlsperger et al., Materialia 2020

X. Wu law (Grain Boundary + Intragrain events)

Based on strain decomposition
1 D approach

Creep

$$\varepsilon = \left(\frac{\sigma}{E} + \varepsilon_p\right) + \boxed{\varepsilon_{gbs}} + \boxed{\varepsilon_v}$$

Elasticity

Plasticity law
for instance

$$\varepsilon_p = K\left(\frac{\sigma}{E}\right)^n$$

GB sliding , dislocation slip
and climb in presence of precipitates in GB
Creep stade I and II

$$\varepsilon_{gbs} = \varepsilon_0 + \phi\dot{\varepsilon}_{ss}t + \frac{\sigma}{\beta^2 H_{gbs}}\left[1 - \exp\left(-\frac{\beta^2\phi H_{gbs}\dot{\varepsilon}_{ss}t}{\sigma(\beta - 1)}\right)\right]$$

$$\dot{\varepsilon}_{ss} = \varphi(1-\beta^{-1})\frac{D\mu b}{kT}\left(\frac{b}{d}\right)^q\left(\frac{l+r}{b}\right)^{q-1}\frac{\sigma(\sigma-\sigma_{ic})}{\mu^2}$$

Dislocation climb and multiplication, intragranular deformation
Creep State III

$$\varepsilon_v = \frac{1}{M}[\exp(M\dot{\varepsilon}_i t) - 1]$$

"M dislocation multiplicator factor?"
→ Taylor factor

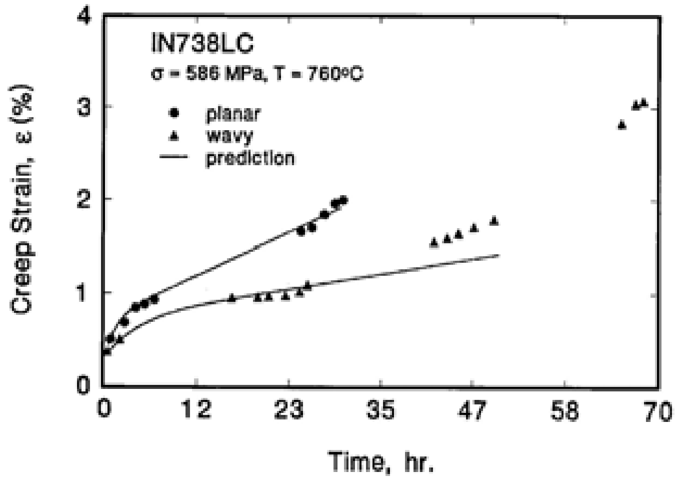
Each eq. is related to dislocation genesis and movement

β microstructure param
D diffusion constant
b Burgers vector
μ shear modulus
r grain boundary precipitate size,
q *GB* precipitate distribution (1 none, 2 discrete, 3 continuous)
p stress exponent for GB sliding
Φ shape factor of GB

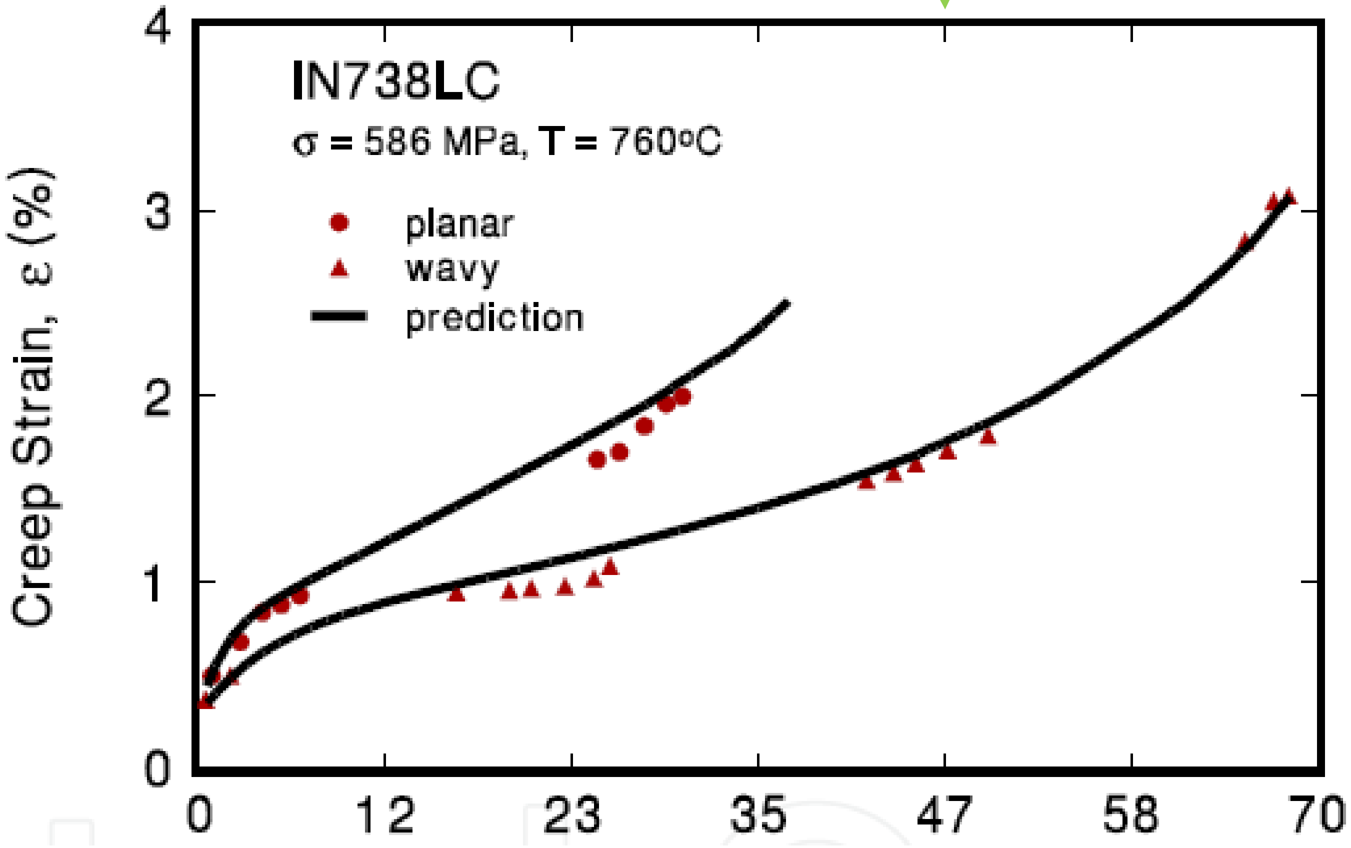
σ_{ic} threshold value → effective stress introduced
σ
d grain size
k Boltzman constant
H_{gbs} *GB* hardening coeff
l grain boundary precipitate spacing

Application of X.Wu creep law

$$\varepsilon = \left(\frac{\sigma}{E} + \varepsilon_p\right) \boxed{+\boxed{\varepsilon_{gbs}} + \varepsilon_v}$$



1. Only GB effect



Wu, X.J. & Koul, A.K. (1996). Modelling creep in complex engineering alloys. In: *Creep and Stress Relaxation in Miniature Structures and Components*, pp. 3-19. The Metallurgical Society, Warrendale, PA.

2. GB effect + precipitate dislocation interaction intra granular

A lack according S. Wu: contribution of creep cavitation (Acta Mat 2022)

X. Wu Chap Life Prediction of Gas Turbine Materials - Intech Gas Turbines edited Gurrappa Injeti 2010

→ Deeper in creep mechanism understanding

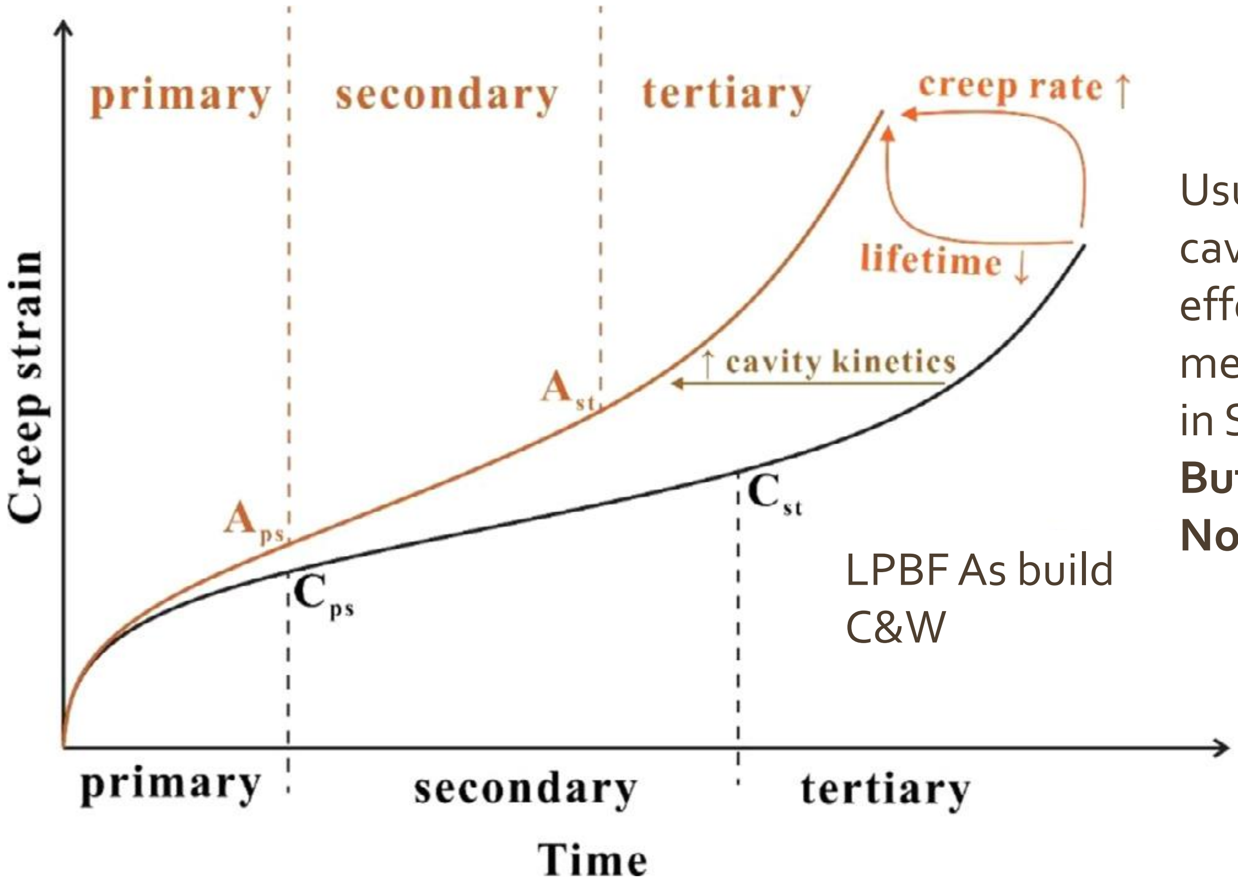
Additive or Cast & Wrought Incoly 718 → ≠ creep behavior

X. Wu, Kock-Mecking-Estrin…
OK for dislocation motion or grain boundary sliding
(if the cavitation kinetics slow)

If cavity density or formation is high,
→ + cavitation creep strain contribution

In AM materials

- High density of vacancies, high porosity
- Compositional inhomogeneity
- Grain anisotropy
- Out of equilibrium microstructure, so evolving with T and t



LPBF As build
C&W

Usually cavitation effect only measurable in Stage III
But
Not in AM

S. Wu et al. Acta Materialia 2022

Creep behavior of heat treated Inconel 718 ? Which microstructure ?

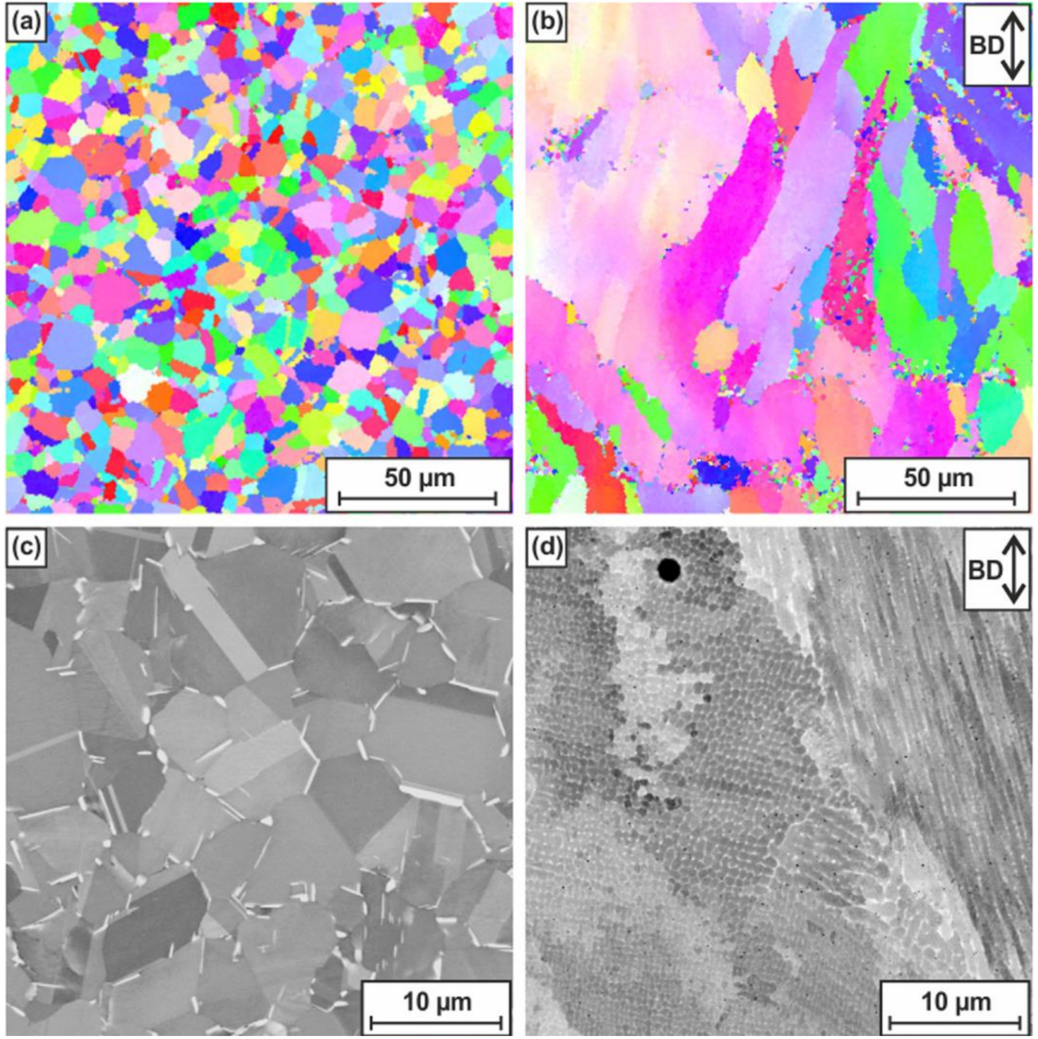
1st example

Completely recrystallized
Average grain 7 µm

Plate light Bright δ particules at GB
Formed during forging
3.5%

Cast & Forged (C&W) + 1.5h 980°C + Aging

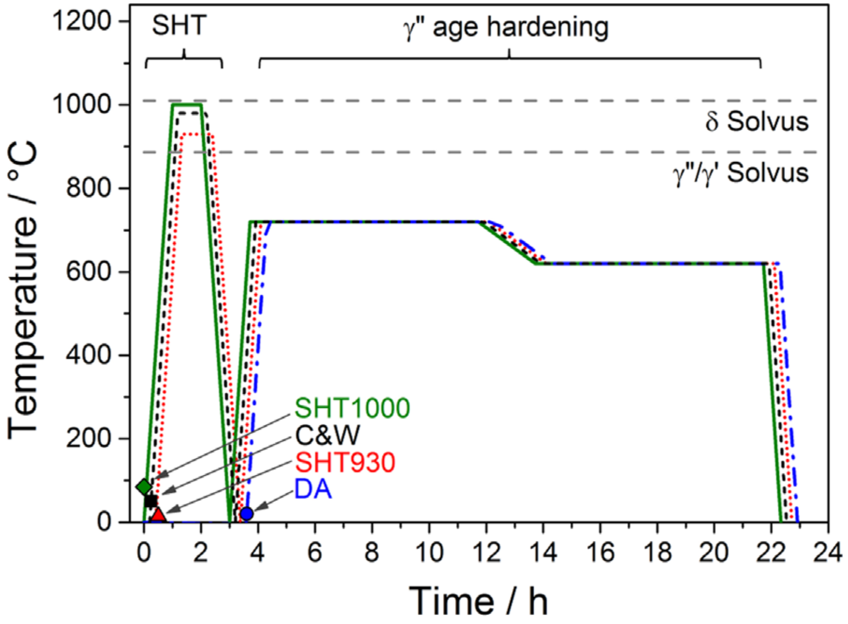
As built LPBF



Large grains (+ subgrains)
Up to 150 µm // building dir.
Up to 30 µm ⊥ building dir.

Fine dendrites
with spacing < 1µm

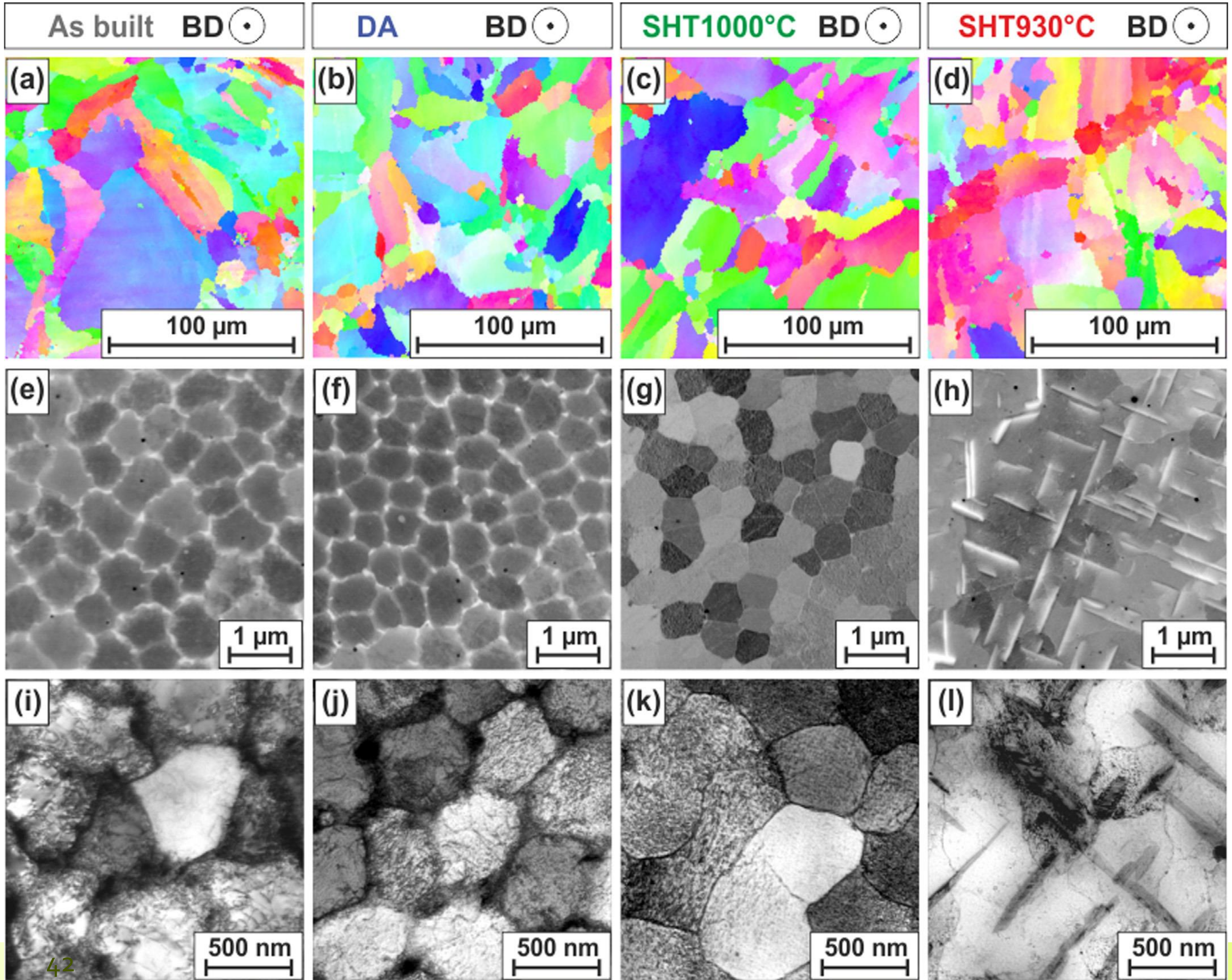
+



(SHT Solution Heat Treatment)

Pröbstle et al. MSEA 2016

Inconel 718: Microstructures LPBF + heat treatment



No γ' γ''

AS built

Aged

Interdendritic region (rich in Nb) + Lave 14
+ High dislocation density around subgrain
No δ

γ' a lot
$\gamma'' \neq$ amount

Nearly no δ

SHT 1000°C + Aged

SHT 930°C + Aged

Interdendritic region
+ Lave 14 dissolved
Low dislocation

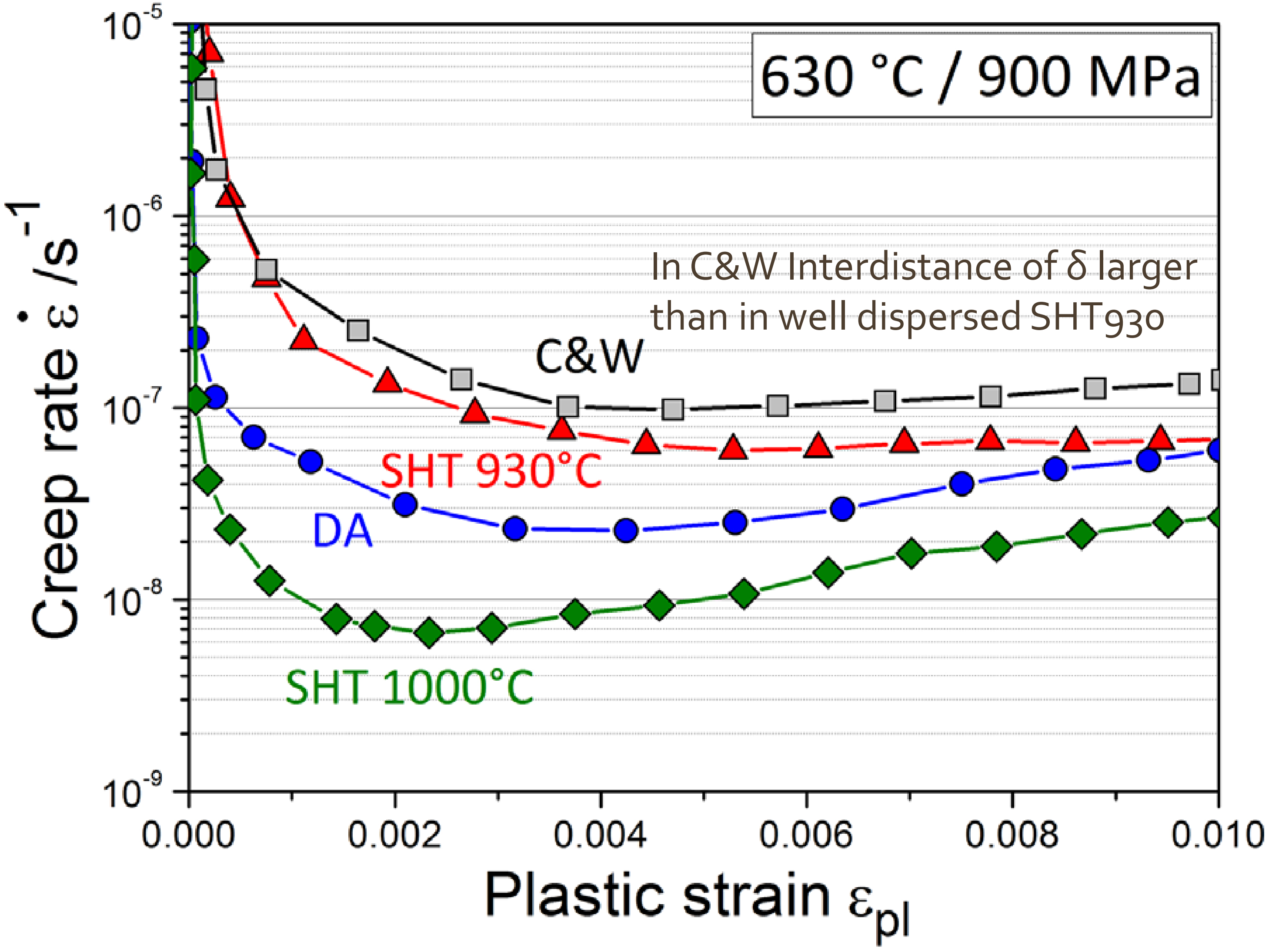
A lot of δ
Intra granular (fine)
+ in High Angle GB (thicker)

Subgrain size $\simeq$ ct 0.6 µm

Pröbstle et al MSEA 2016

Creep behavior of Inconel 718 LPBF + heat treatment

Experiments: compression 630°C
(TP such that no over aging and strong micro. evolution like recrystallisation)



γ'' --> creep strength
different amount and length

δ (high Nb) → less γ' γ''
+Thick δ → vacancy nucleation
→ SHT 930 not optimal

Laves (high Nb)
→ less γ' γ'' but higher than SHT 930
→ Aged state better

No δ, no Laves, low dislocations
Larger γ''size in addition to higher volume
But sub grains less stable

LPBF Subgrain size ≃ ct at 630°C

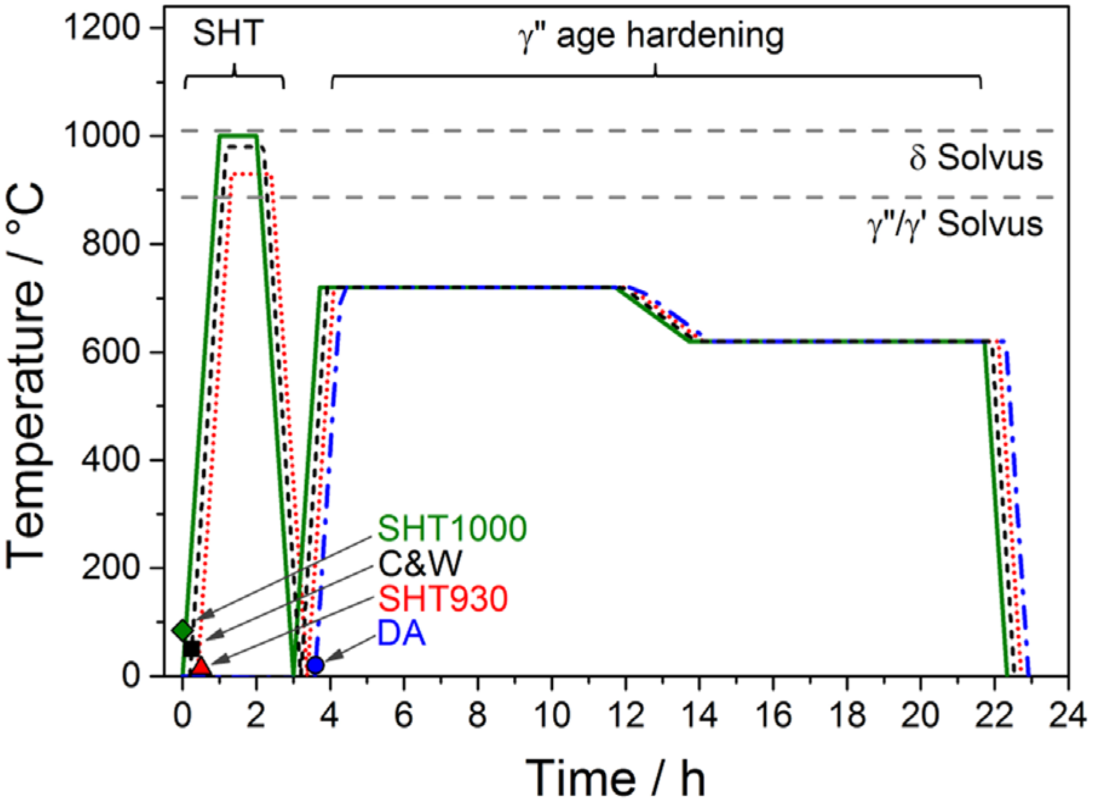
Sub grain generated by high creep stress will be smaller

Pröbstle et al. MSEA 2016

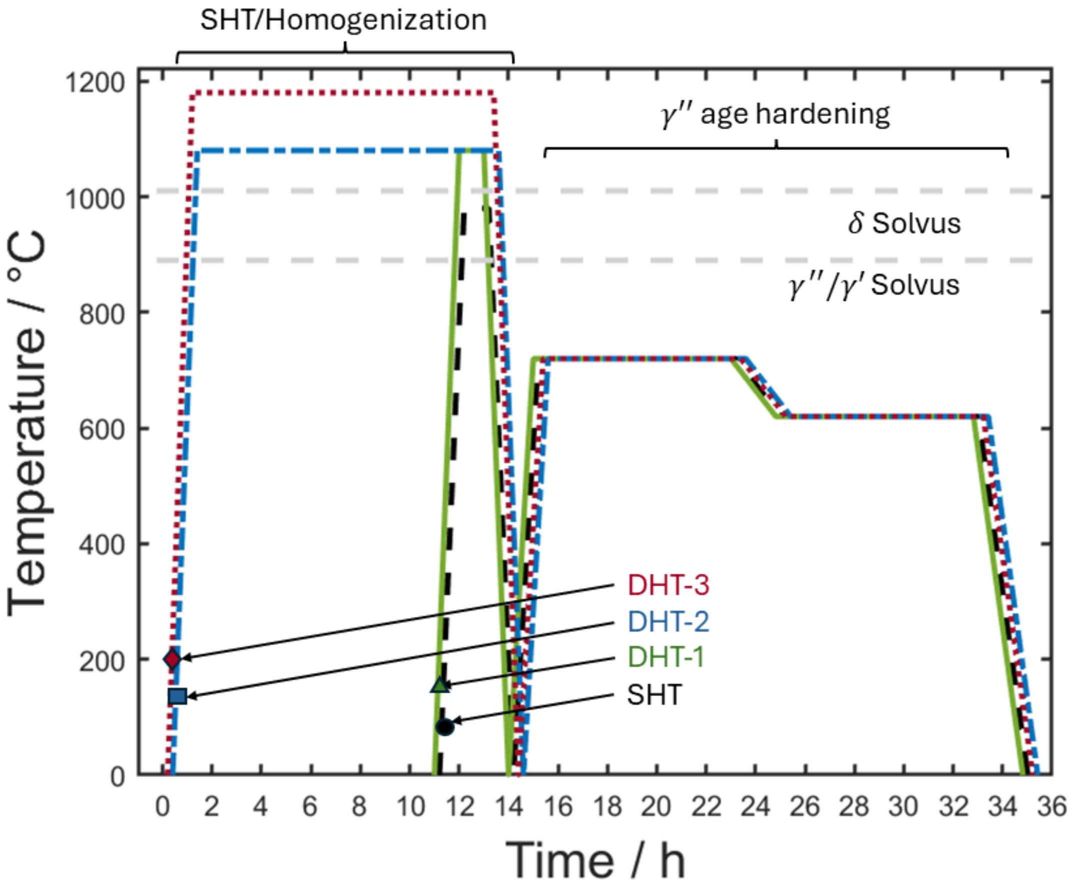
Creep behavior of Inconel 718 LPBF + Post Heat treatments

2nd example

Experiments: tension 630°C
(strong micro. evolution like recrystallisation)



≠



Creep tests
Compression

Pröbstle et al. MSEA 2016
LPBF 175W 620mm/s

All DHT are performed > 1050°
→ recrystallisation and no more subgrains
according. Zhang MSEA 2015

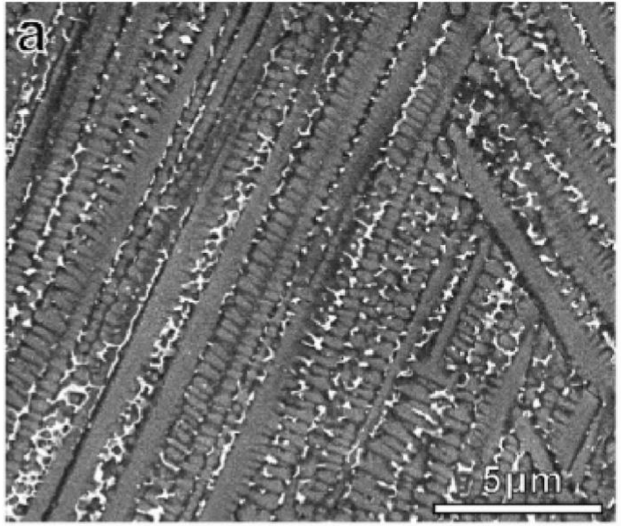
DHT
designed heat
treatment

Pröbstle et al. MSEA 2016

S. Wu et al. MSEA 2022

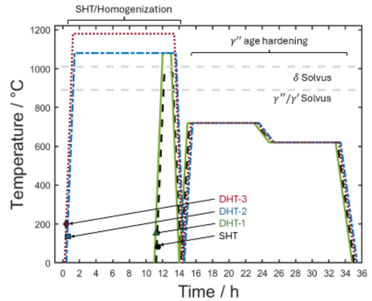
Inconel 718: Microstructures LPBF+ Heat Treatment

As Built LPBF

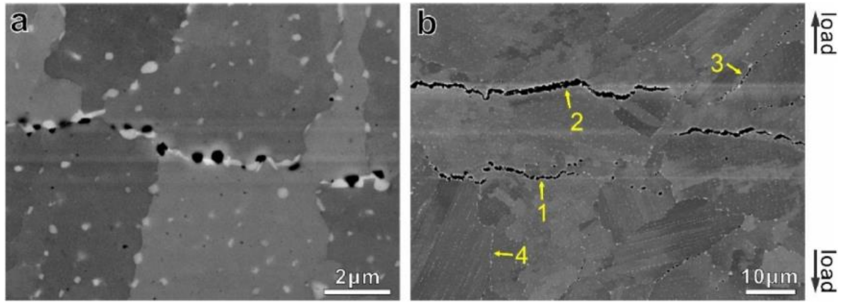


Dendritic structure and inter-dendritic Laves phase

LPBF manufactring param: 285 W laser power, 960mm/s scan speed



GB particles dissolution → **cavity nucleation** (mostly in GB⊥ building dir.)

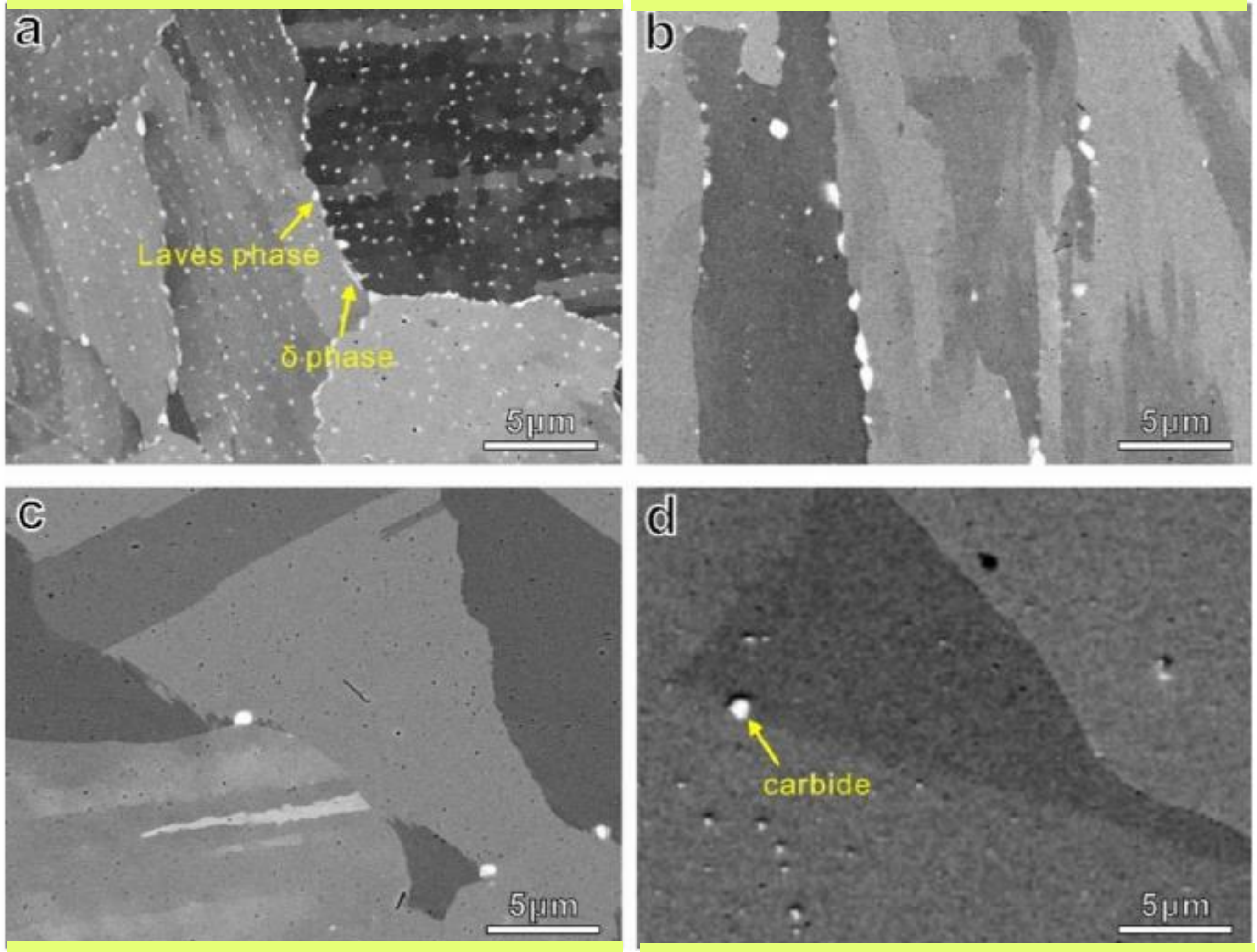


Laves + δ in GB

Laves + δ in GB↘, NbC present,

SHT (980°C° 1h)

DHT1 (1080 C° 1h)



DHT2 (1080 C° 12h)

DHT3 (1180 C° 1h)

Laves + δ diappear GB, NbC present

S. Wu et al. MSEA 2022

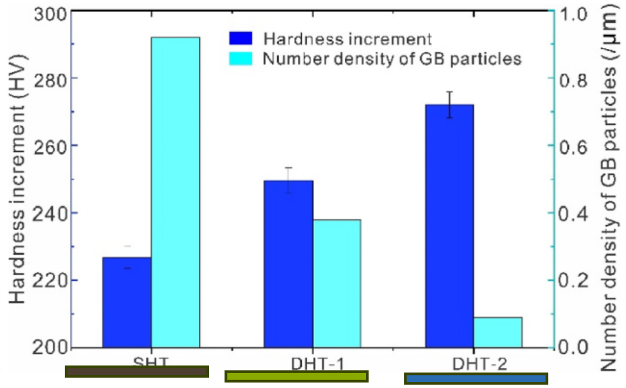
Inconel 718: Microstructures LPBF+ Heat Treatment

SHT, DHT1 : columnar grain structure
low angle GBs
Grain aspect ratio ≃ 3.26

DHT2 and DHT3 :
recrystallized equiaxed grains
high angle GBs
Grain aspect ratio ≃1
high fraction of annealing twins
(effect higher for DHT2
grain growth decreases them)

DHT2: average grain size 80μm

DHT3 : average grain size 280μm



$\gamma'' \propto$ hardness

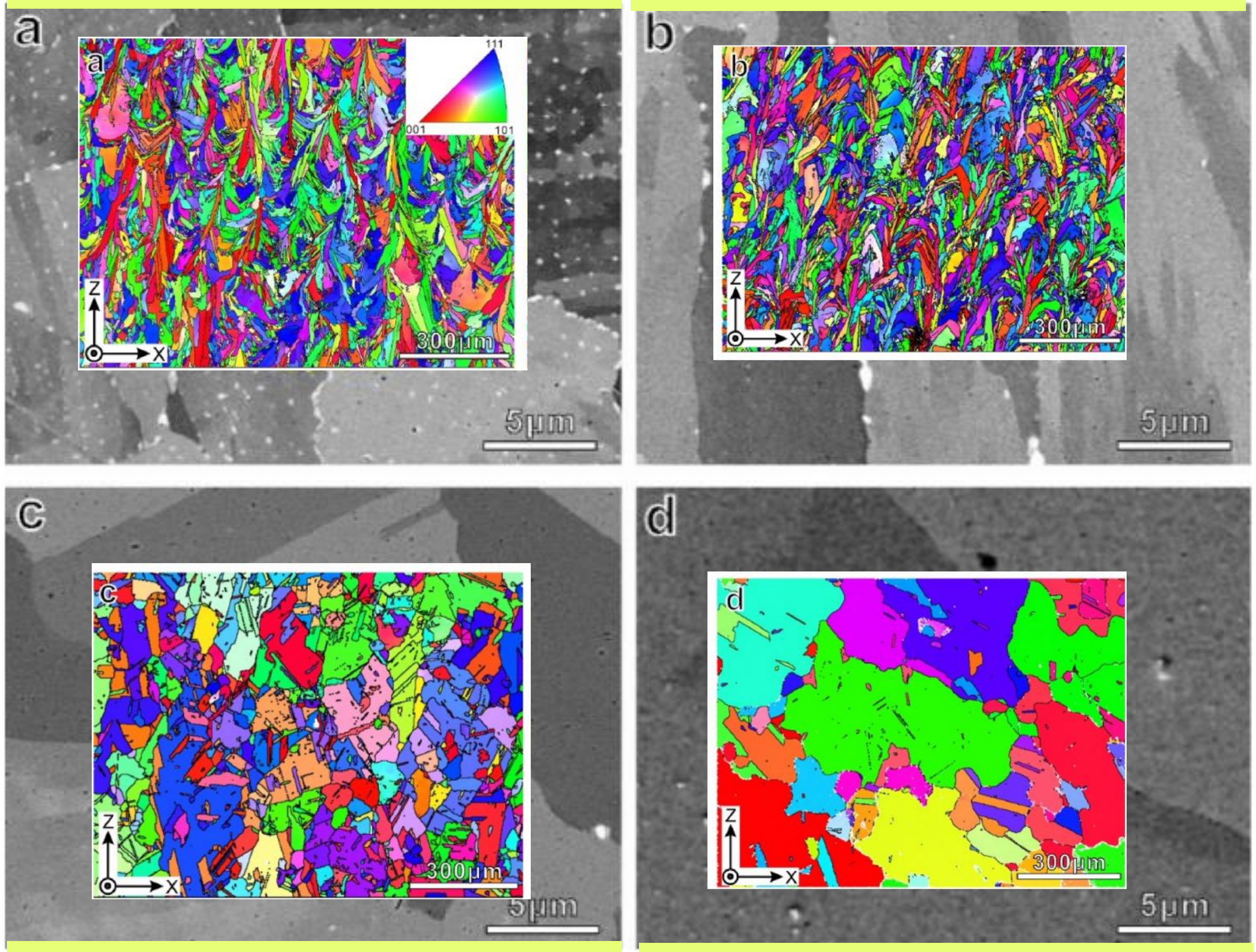
Related to dissolution of GB particles

Laves + δ in GB

Laves + δ in GB↘ NbC present,

SHT (980°C° 1h)

DHT1 (1080 C° 1h)



DHT2 (1080 C° 12h)

DHT3 (1180 C° 1h)

S. Wu et al. MSEA 2022

Laves + δ disappear GB, NbC present

Creep behavior of Inconel 718 : S. Wu model

$t_r \propto 1/(N_p + N_{gb})$

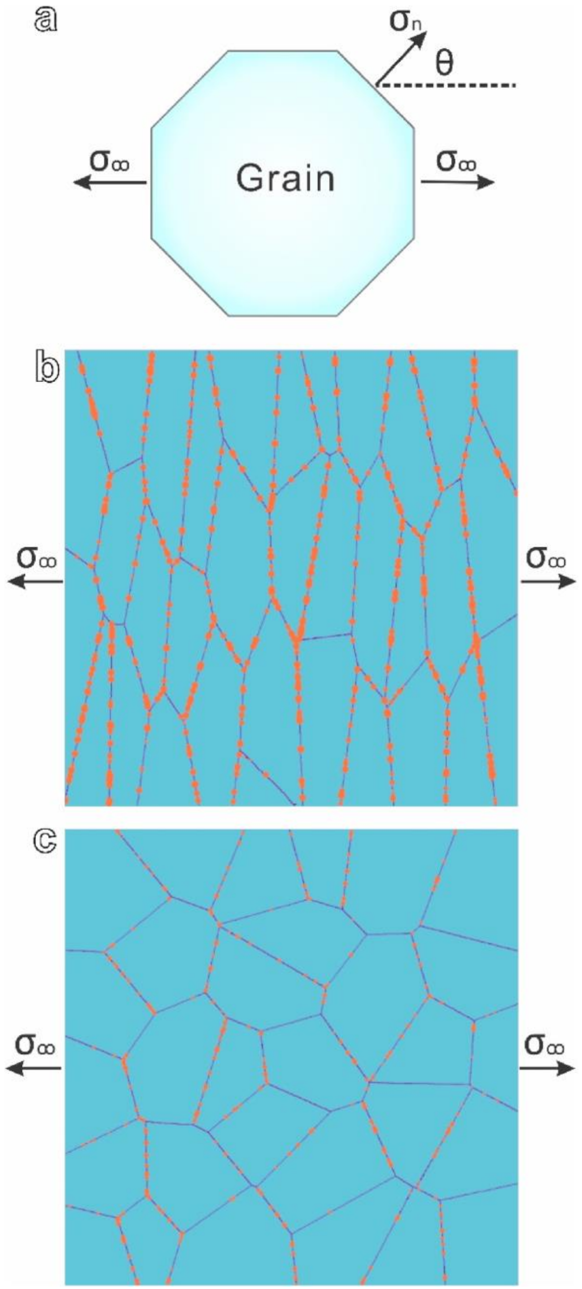
N_p potential nucleation site density ≃ GB particle density well oriented

→ **grain shape effect !!!**

N_{gb} triple points and GB ledge density
(identified from difference between SHT and DHT1)

$$\dot{\epsilon}_m^c \propto \frac{\emptyset_m \lambda_m}{h} \sinh\left(\frac{\sigma b^2 \lambda_m}{MkT}\right)$$

$\emptyset_m$	Volume fraction precipitate
λ_m	Average dislocation glide distance
h	Dislocation climb distance against precipitates
b	Burgers vectir
M	Taylor factor



effect of GB particles (SHT>DHT1>DHT2 & DHT3)
γ'' density - intra granular effect (larger in DHT2 & DHT3>DHT1>SHT)
Grain shape (Larger in SHT and DHT1 + anisotropy) as cavitation if orientation of GB OK

S. Wu et al. MSEA 2022

Creep behavior of Inconel 718 : S. Wu model

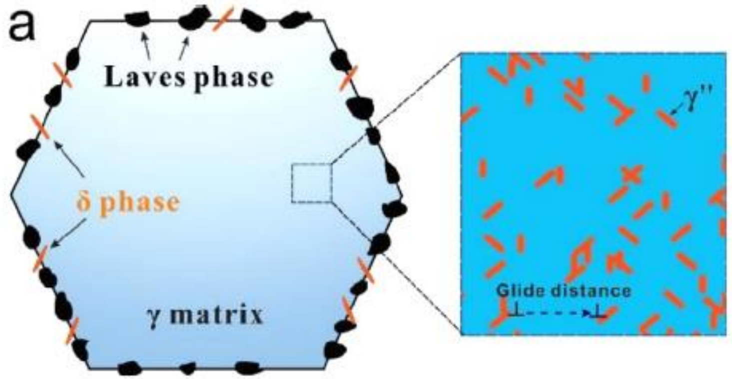
2nd example

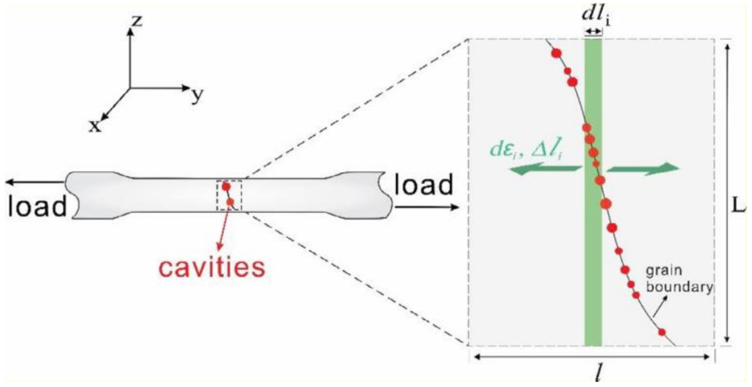
Total set of equations to model

- Dislocation motion (glide + climb) and GB sliding
- Cavitation kinetics

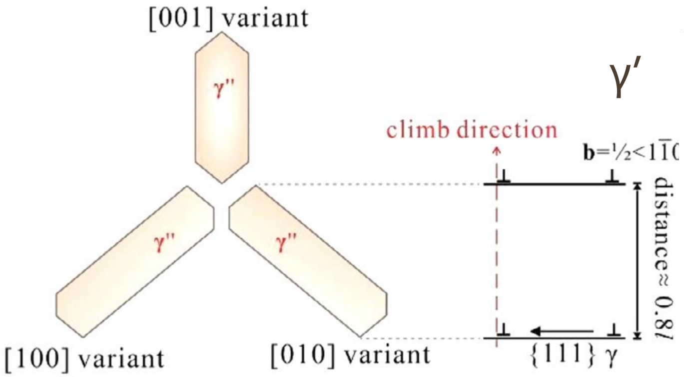
Concept of effective stress due to damage

Idealized Microstructure

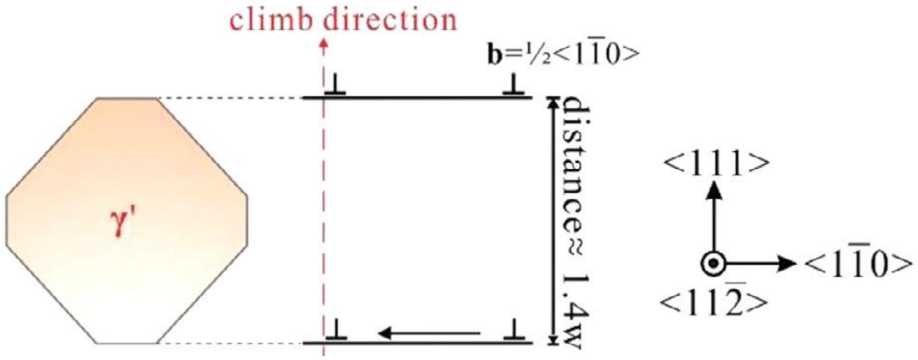




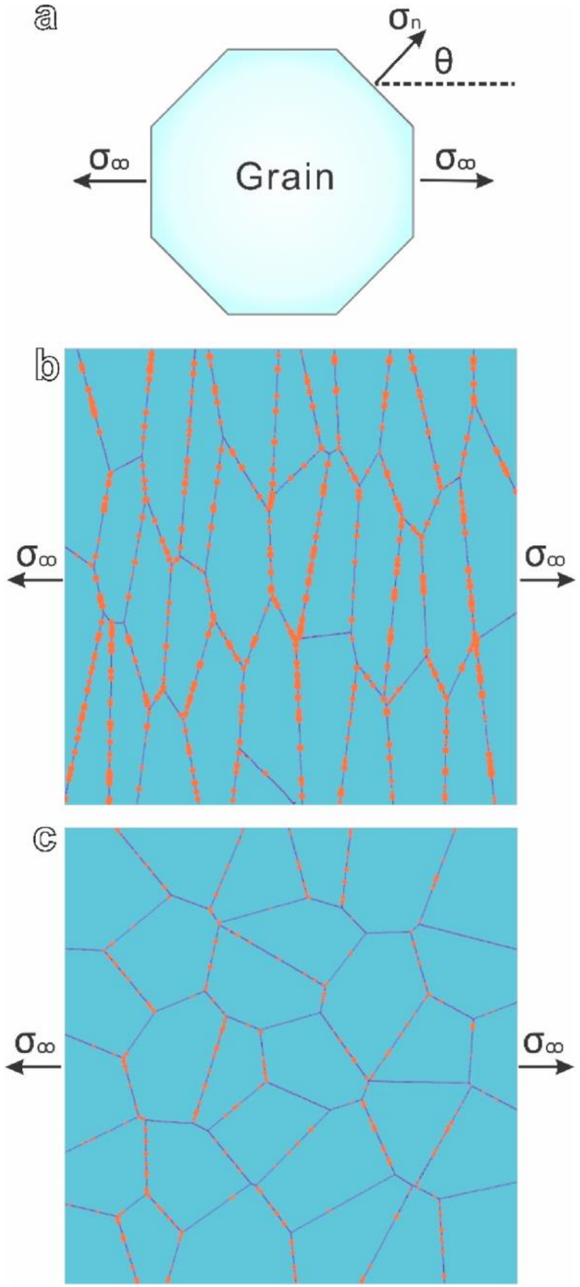
3 Variants of γ''



γ'



Estimation of climb distance for dislocation



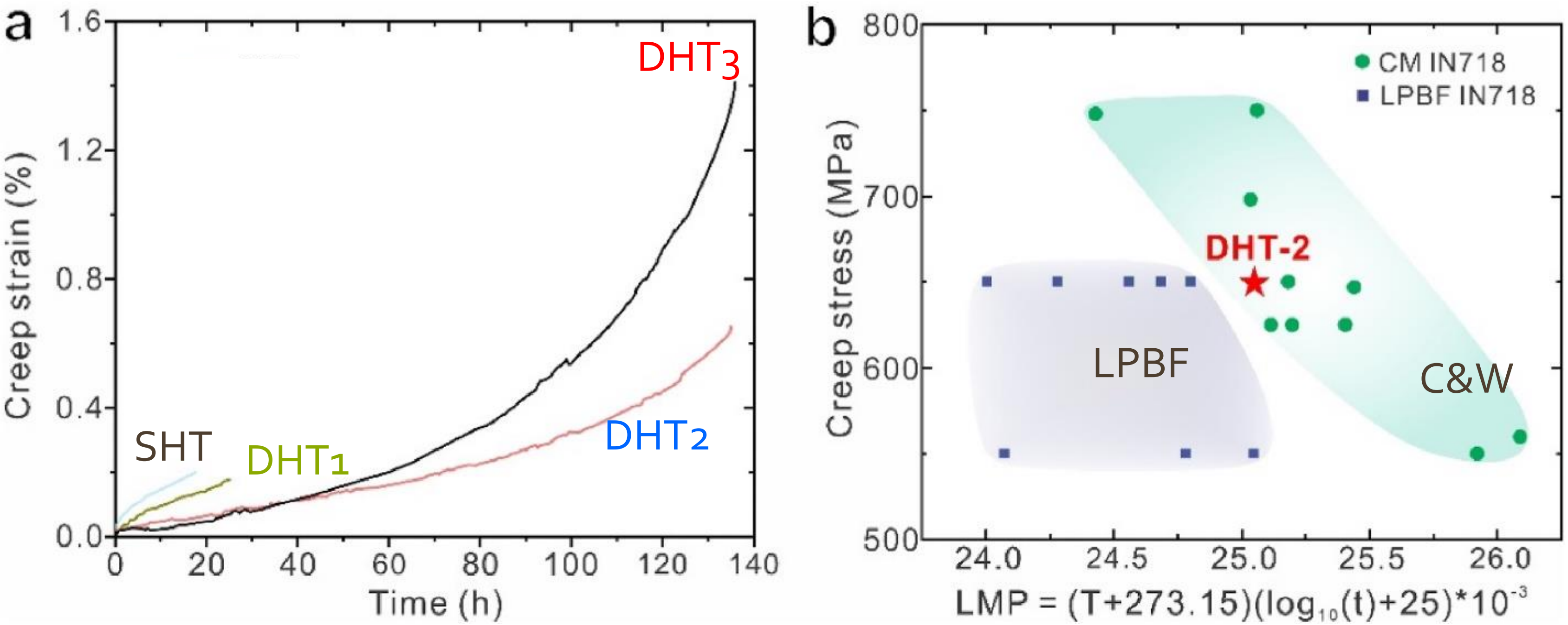
S. Wu et al. Acta Materialia 2022 (Model Dislocation densities + Cavitation ≃ Ghoniem, Yadav, Riedlsperger …)

Creep behavior of Inconel 718
LPBF + heat treatment

Experiments: tension 630°C
(strong micro. evolution like recrystallisation)

Which dominant mechanism ?

GB sliding dominant creep mechanism (cavity formation at triple junction points)
Dislocation dominant creep mechanism (cavity formation due to dislo pile up at GB or GB ledge or at subgrains boundary)



T_r of DHT2 = DHT3
→ GB non dominant mechanism
as strong different grain size 80 -> 280 µm

Dislocation glide-climb =main mechanism

Cavitation ∝ GB particle number

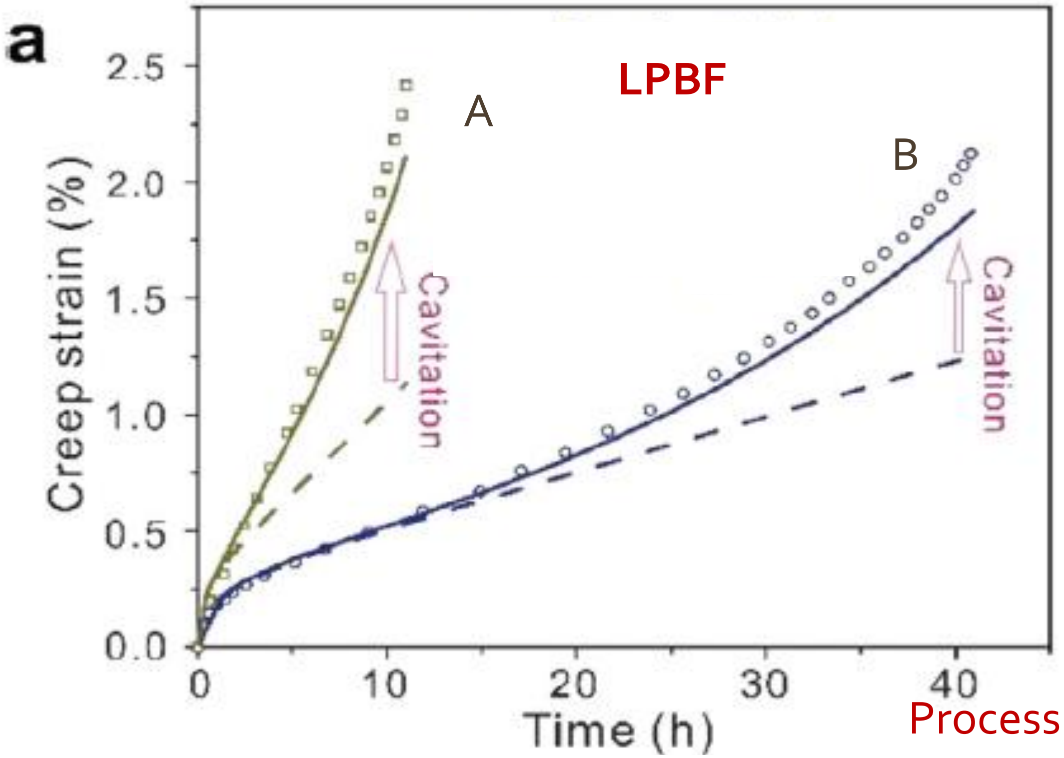
SHT>DHT1> DHT2

S. Wu et al. MSEA 2022

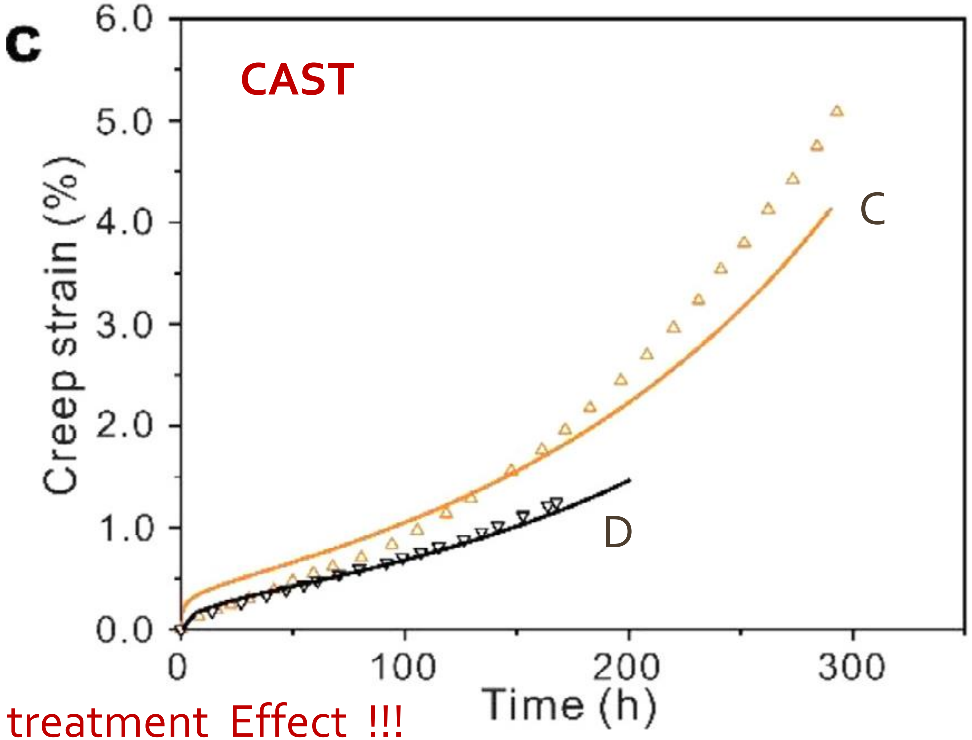
Creep behavior of Inconel 718: S. Wu model's result

3rd example

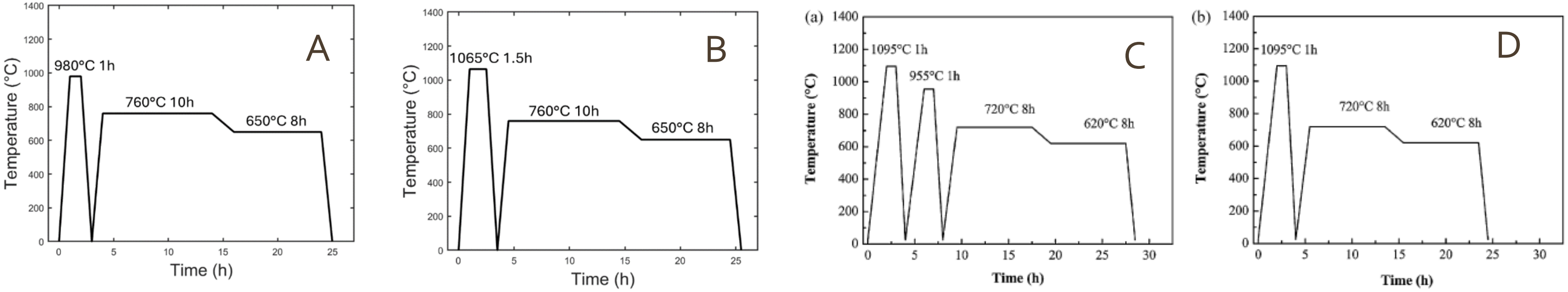
650 Mpa 650 °C



625 Mpa 650 °C



Process and Heat treatment Effect !!!



Prediction
--- without cavitation
__ with cavitation
Experiment o o o o o

Model S. Wu et al. MSEA 2022 / Exp Shi et al. MSEA 2019 and Kuo et al. MSEA 2009

Contents

Solar receivers - Walloon Region projects (Experiments + Modeling)

MSM

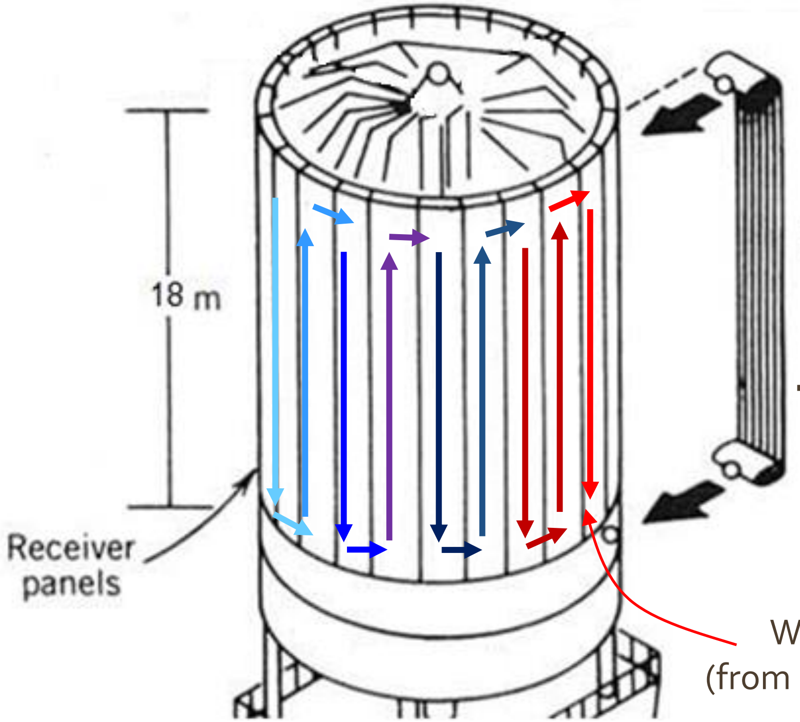
LIÈGE université
Sciences Appliquées

CRM GROUP

John Cockerill

LITHCOTE

RÉGION WALLONNE
DE BELGIQUE



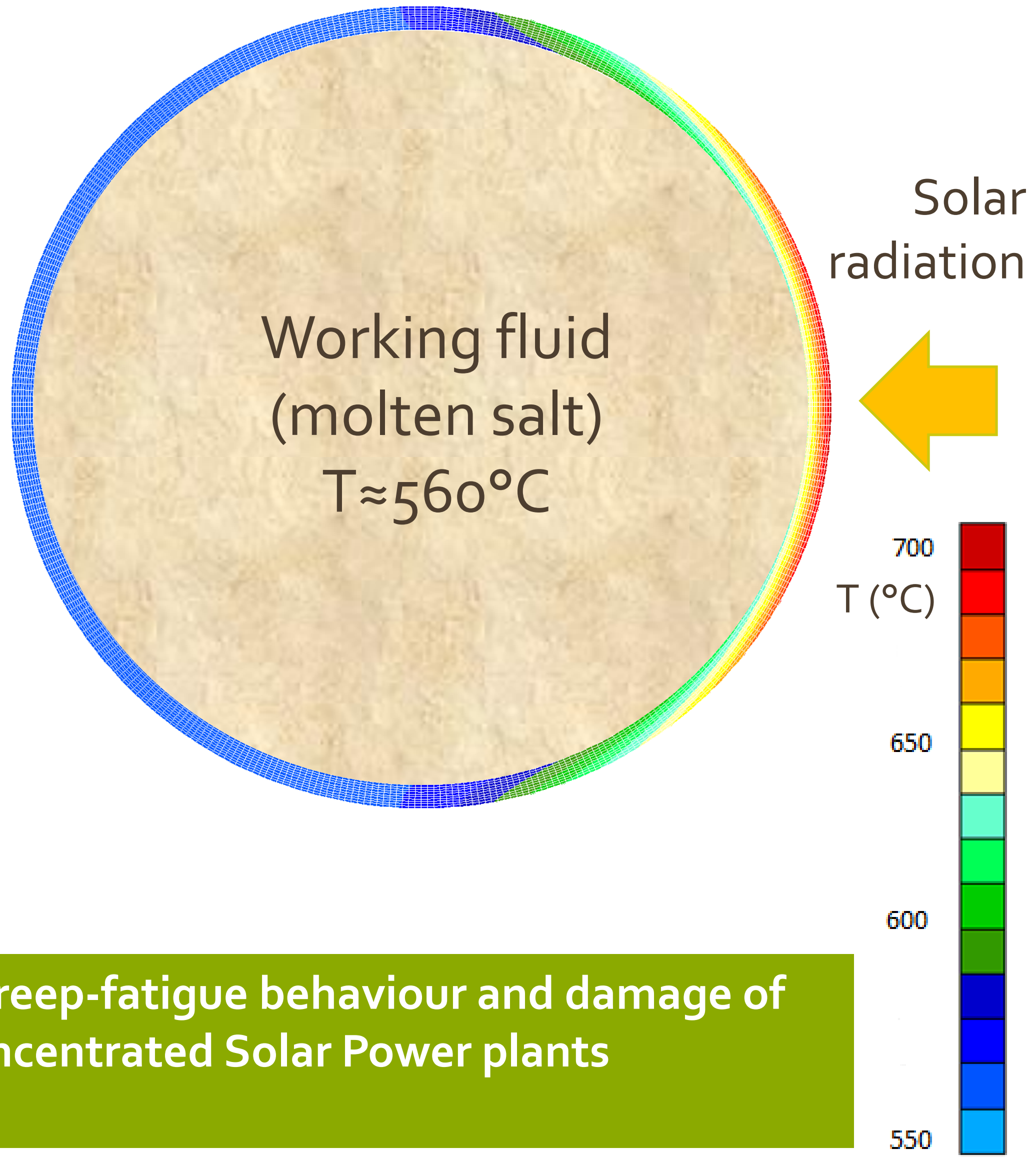
Working fluid
(from 330°C to 565°C)

Solar receiver
(source : W.B.Stine, R.W.Harrigan, Solar Energy Systems Design)

Tube:
Ø 50 mm
t=1.5 mm

Panel of tubes manufactured from nickel alloy sheet (Haynes 230)
(source : CMI Solar)

The tubes



Temperature distribution in a tube
(Lagamine FE code)

- **Fatigue + creep**
- **Extreme Thermo-mechanical loading** (Haynes 230)
- **Advanced model**

Thermomechanical modelling of the creep-fatigue behaviour and damage of Nickel-alloy receiver tubes used in Concentrated Solar Power plants
Morch, Hélène PhD Uliege 2022

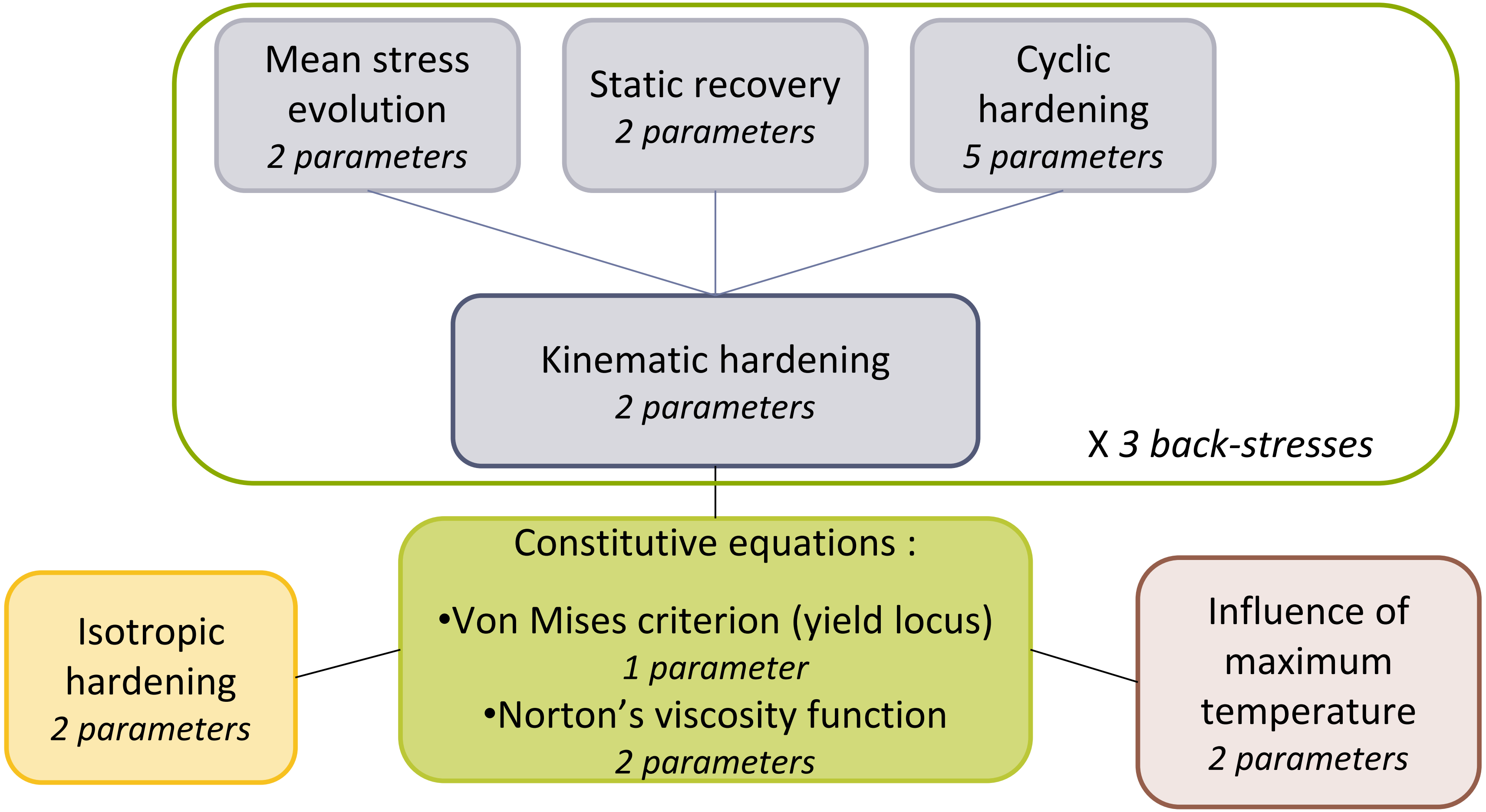
"Morch law"

https://hdl.handle.net/2268/295588

Advanced damage Chaboche coupled model

Effect of tensile and compressive hold times on the rupture behavior of nickel-based alloy 230 at 700°C submitted… Morch et al.

31 Equations
to solve…



Mean stress evolution
2 parameters

Static recovery
2 parameters

Cyclic hardening
5 parameters

Kinematic hardening
2 parameters

X *3 back-stresses*

Constitutive equations :

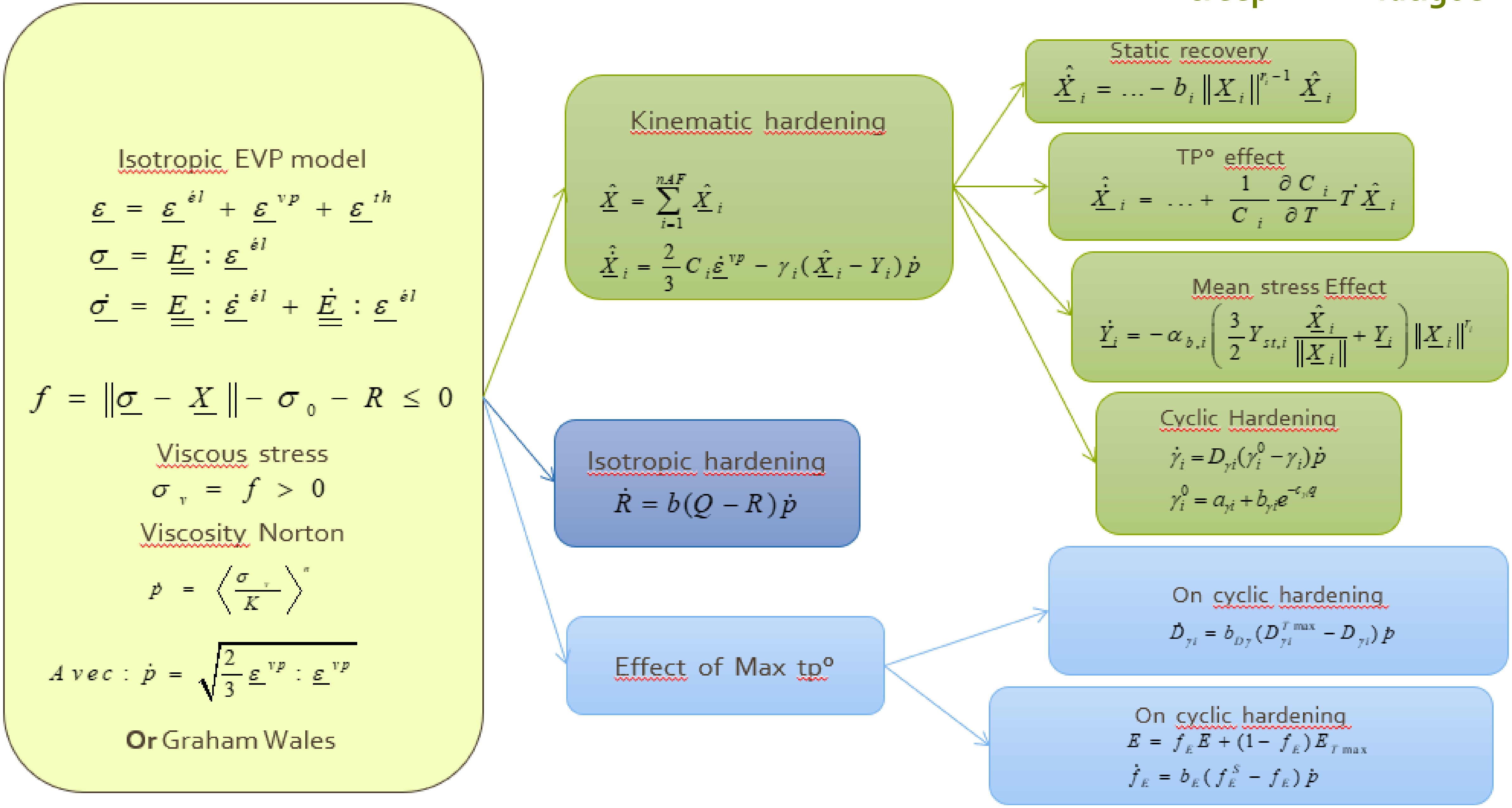
- Von Mises criterion (yield locus)
  1 parameter
- Norton's viscosity function
  2 parameters

Isotropic hardening
2 parameters

Influence of maximum temperature
2 parameters

→ ~~40~~ 28 parameters→ **Efficient temperature dependence of parameters for thermo-mechanical finite element modeling of alloy 230** Morch et al. *European Journal of Mechanics – A/Solids, 85*, p. 104-116

Morch law: 1st version uncoupled , 2nd coupled… D_{creep} + $D_{fatigue}$



Isotropic EVP model

$$\underline{\varepsilon} = \underline{\varepsilon}^{\acute{e}l} + \underline{\varepsilon}^{vp} + \underline{\varepsilon}^{th}$$

$$\underline{\sigma} = \underline{\underline{E}} : \underline{\varepsilon}^{\acute{e}l}$$

$$\dot{\underline{\sigma}} = \underline{\underline{E}} : \dot{\underline{\varepsilon}}^{\acute{e}l} + \dot{\underline{\underline{E}}} : \underline{\varepsilon}^{\acute{e}l}$$

$$f = \|\underline{\sigma} - \underline{X}\| - \sigma_0 - R \leq 0$$

Viscous stress

$$\sigma_v = f > 0$$

Viscosity Norton

$$\dot{p} = \left\langle \frac{\sigma_v}{K} \right\rangle^n$$

$$Avec : \dot{p} = \sqrt{\frac{2}{3} \underline{\varepsilon}^{vp} : \underline{\varepsilon}^{vp}}$$

Or Graham Wales

Kinematic hardening

$$\hat{\underline{X}} = \sum_{i=1}^{nAF} \hat{\underline{X}}_i$$

$$\dot{\hat{\underline{X}}}_i = \frac{2}{3} C_i \dot{\underline{\varepsilon}}^{vp} - \gamma_i (\hat{\underline{X}}_i - \underline{Y}_i) \dot{p}$$

Isotropic hardening

$$\dot{R} = b(Q - R)\dot{p}$$

Effect of Max tp°

Static recovery

$$\dot{\hat{\underline{X}}}_i = \ldots - b_i \|\underline{X}_i\|^{r_i - 1} \hat{\underline{X}}_i$$

TP° effect

$$\dot{\hat{\underline{X}}}_i = \ldots + \frac{1}{C_i} \frac{\partial C_i}{\partial T} \dot{T} \hat{\underline{X}}_i$$

Mean stress Effect

$$\dot{\underline{Y}}_i = -\alpha_{b,i} \left(\frac{3}{2} Y_{st,i} \frac{\hat{\underline{X}}_i}{\|\underline{X}_i\|} + \underline{Y}_i \right) \|\underline{X}_i\|^{r_i}$$

Cyclic Hardening

$$\dot{\gamma}_i = D_{\gamma i}(\gamma_i^0 - \gamma_i)\dot{p}$$

$$\gamma_i^0 = a_{\gamma i} + b_{\gamma i} e^{-c_{\gamma i} q}$$

On cyclic hardening

$$\dot{D}_{\gamma i} = b_{D\gamma} (D_{\gamma i}^{T\max} - D_{\gamma i}) \dot{p}$$

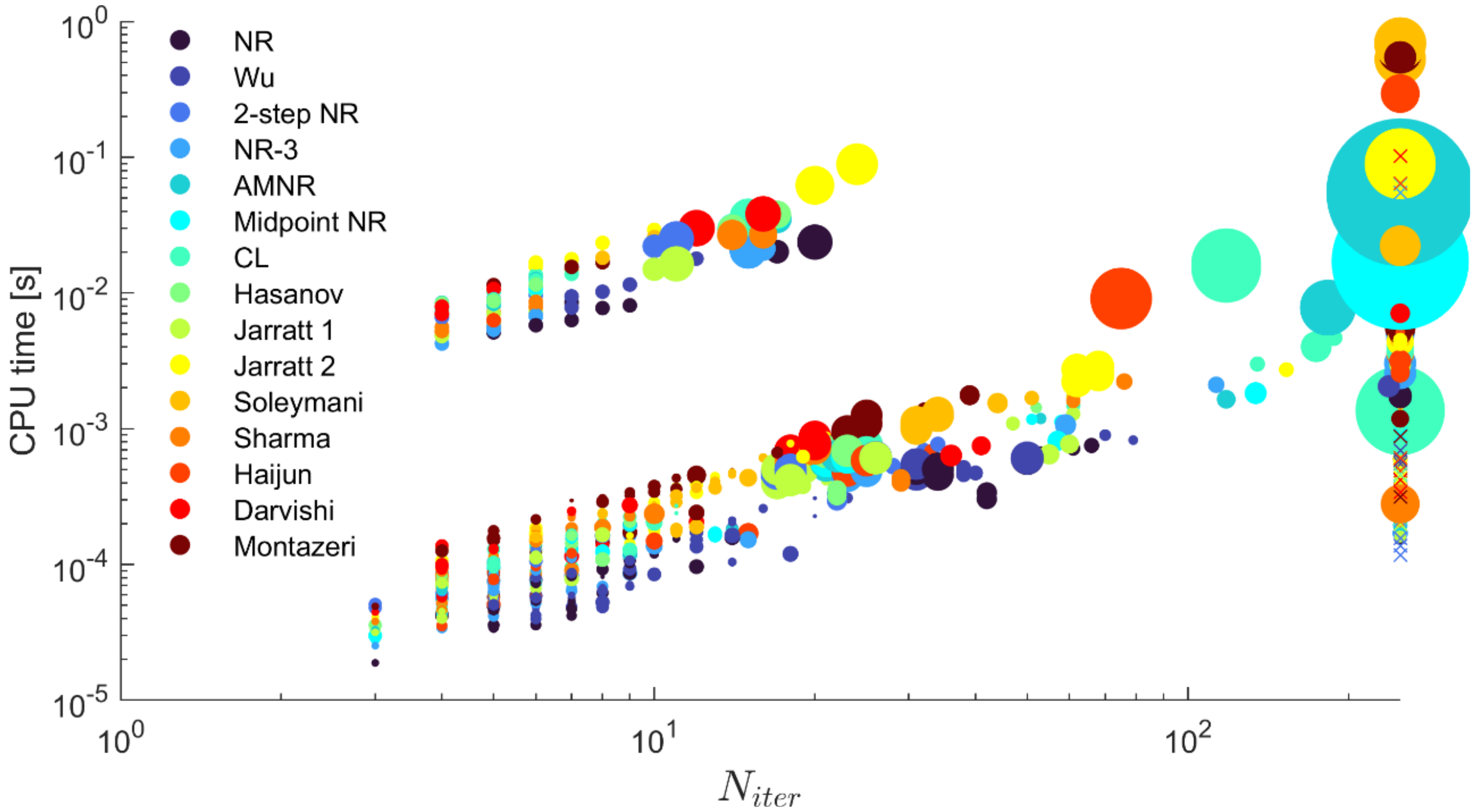
On cyclic hardening

$$E = f_E E + (1 - f_E) E_{T\max}$$

$$\dot{f}_E = b_E (f_E^S - f_E) \dot{p}$$

Study of optimal resolution → Newton Raphson !!!

Analysis of different resolution approach



Iteration number versus CPU time to solve the equation system

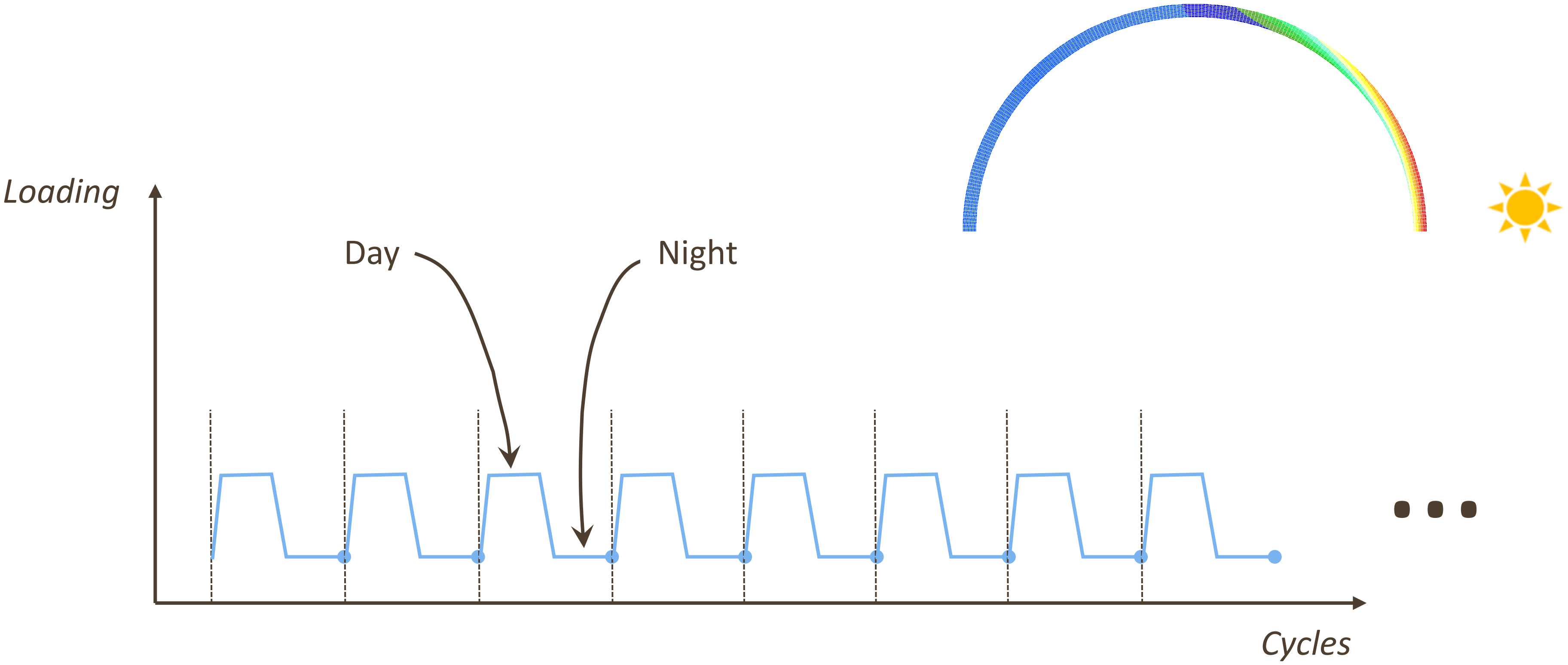
A review of
higher order Newton type methods and
the effect of numerical damping

for the solution of

an advanced coupled Lemaitre damage model

Morch et al. *Finite Elements in Analysis and Design, 209*, p. 103801

Cycle jump approach

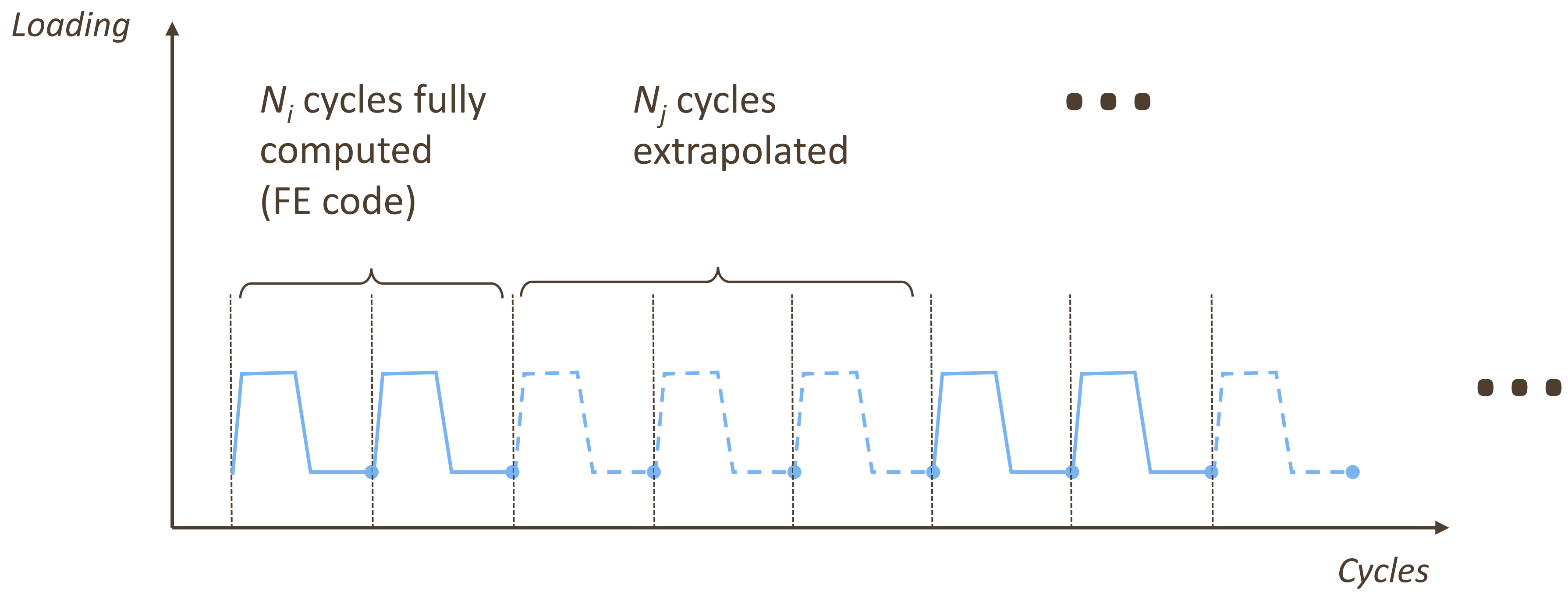


Target: ▶10 000 cycles
(~25 years)

▶18m long tube
(~200 000 FE, 10^6 DOFs)

Duchêne et al. ICTP 2023
Conf proc.

Cycle jump approach



Target: ▶10 000 cycles (~25 years)

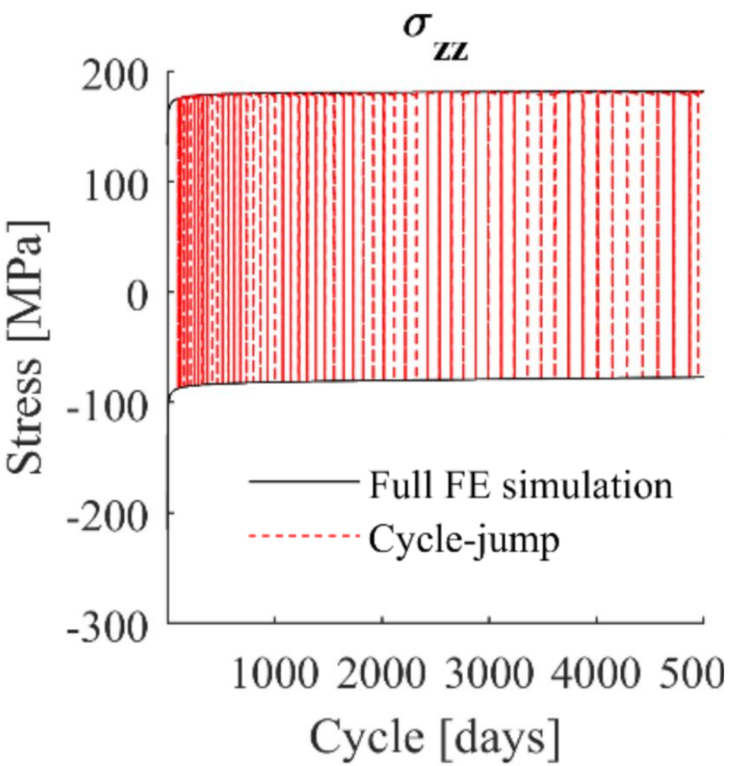
▶18m long tube (~200 000 FE, 10^6 DOFs)

This study: ▶ 5 000 cycles

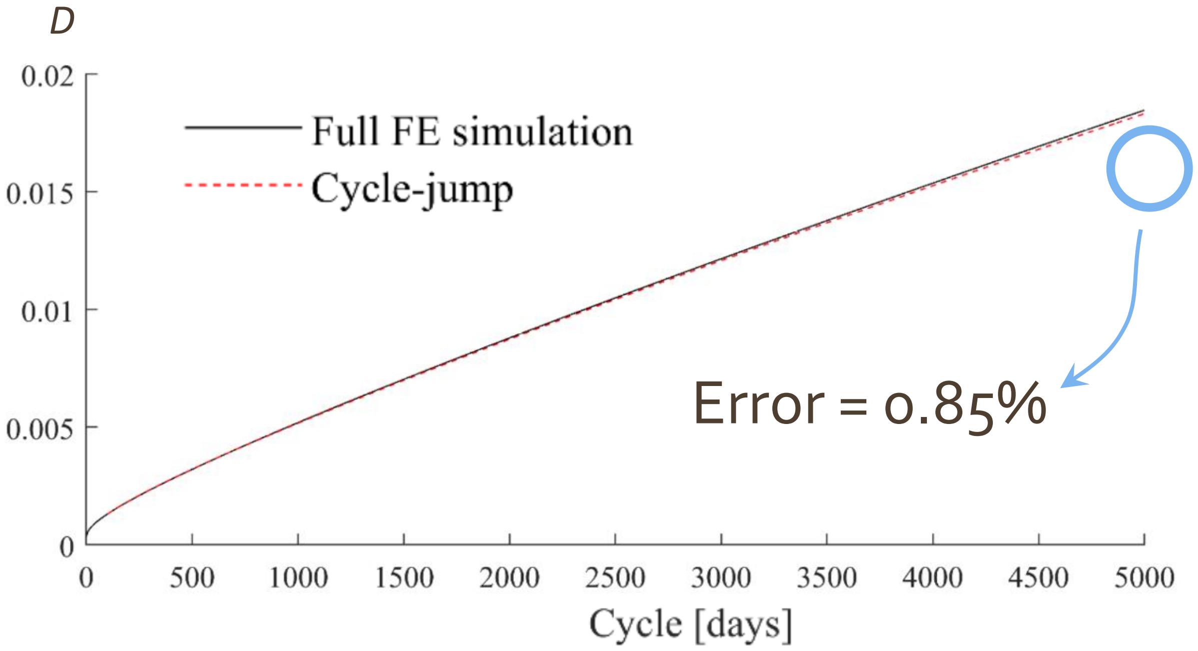
▶ 1 slice of the tube (300 FE, ~3000 DOFs)

Duchêne et al. ICTP 2023 Conf proc.

Cycle jump: optimum parameters



Total Damage



Error = 0.85%

	CPU time (hours)
Full FE computation	104
Optimum Cycle jump	11

- 5 000 cycles
- 1 slice of the tube (300 FE, ~3000 DOFs)

Duchêne et al. ICTP 2023 Conf proc.

Contents

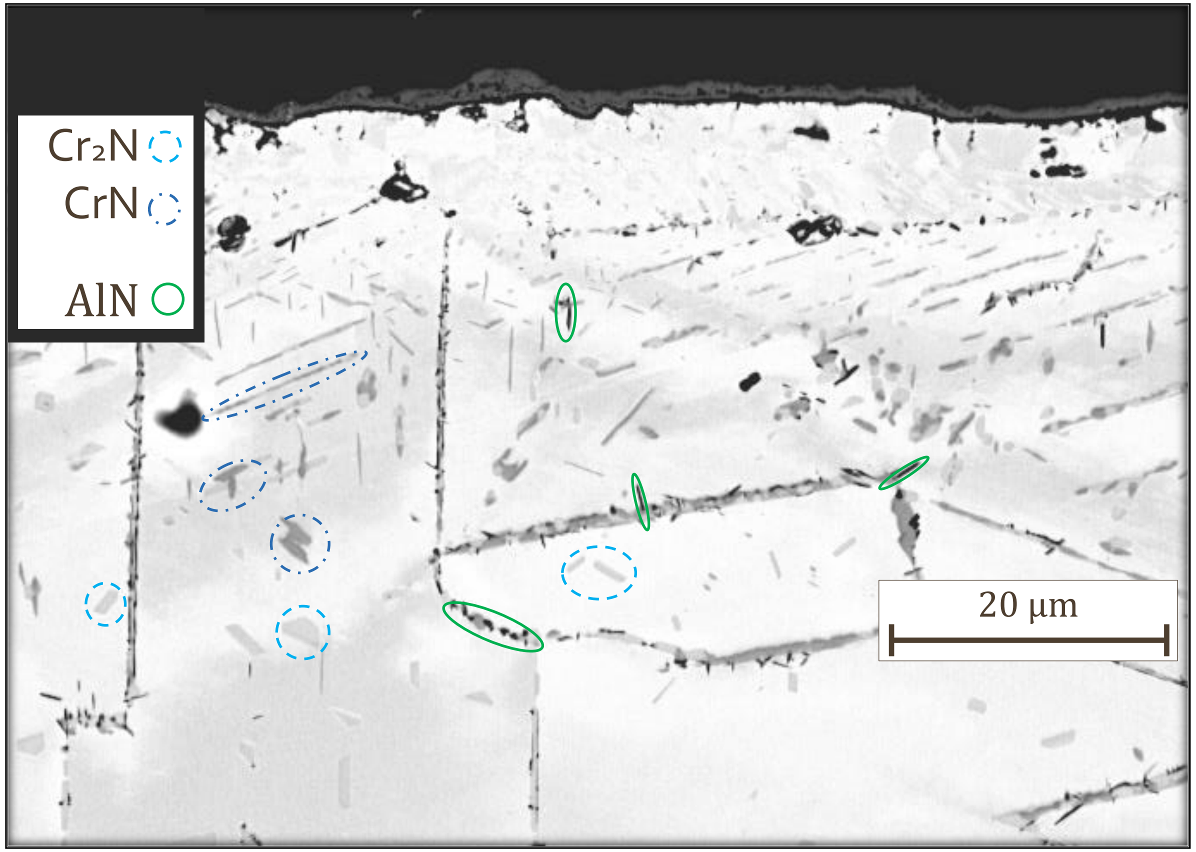
Environmental effects on creep: nitridation

800H

Long-term (>1000h)
high-temperature exposure
high-N_2 environment (e.g., air)

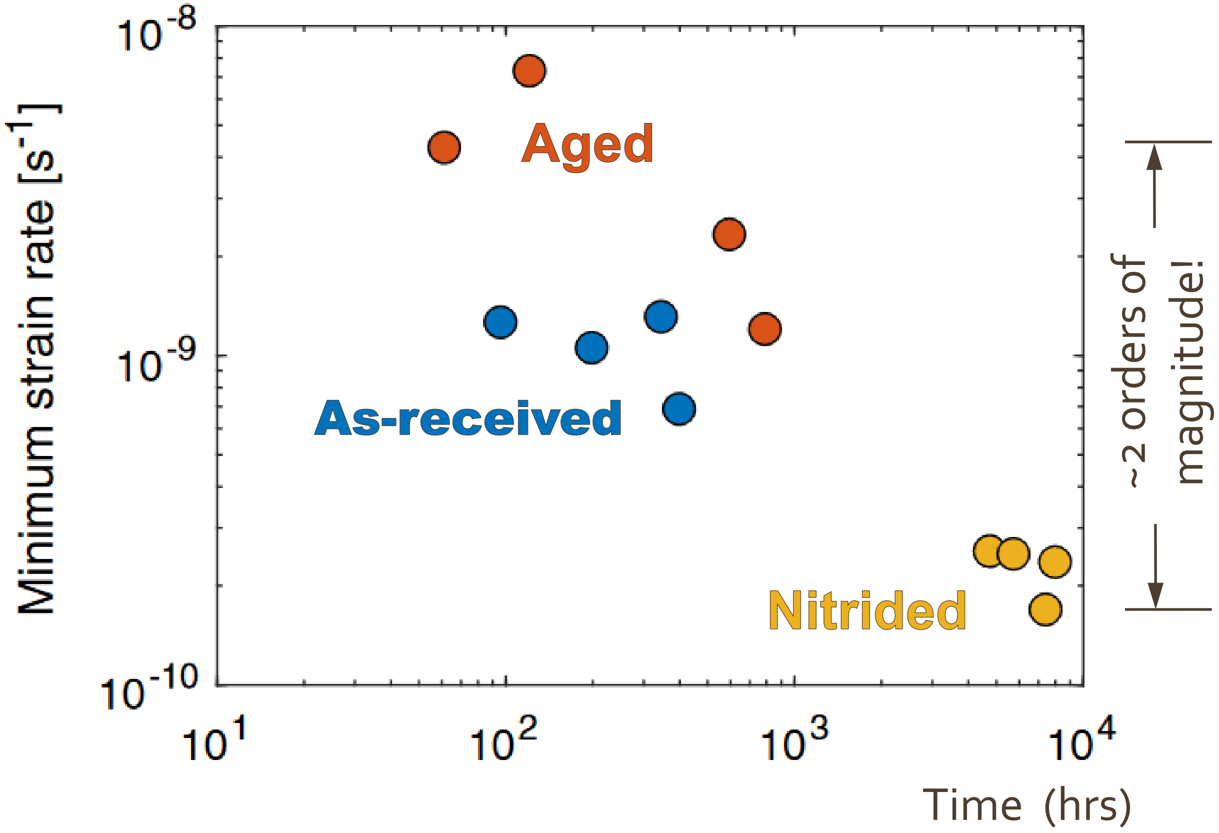
=

Nitridation
Precipitation of:
AlN, CrN, Cr_2N



Nitridation → creep hardening

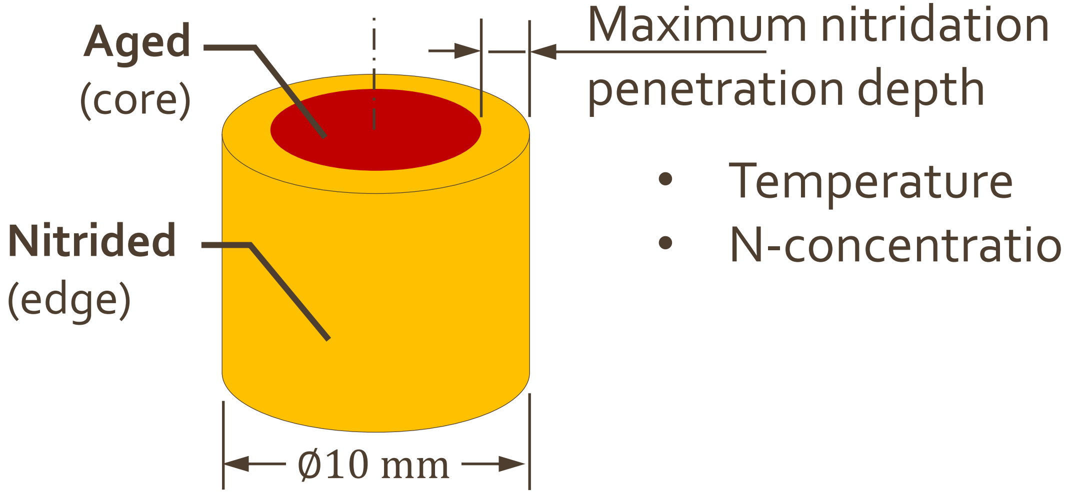
At 1000°C and 8 MPa



A.M. Young et al., 2023

Environmental effects on creep: nitridation

FE simulation of nitridation effect (Lagamine code Uliege)

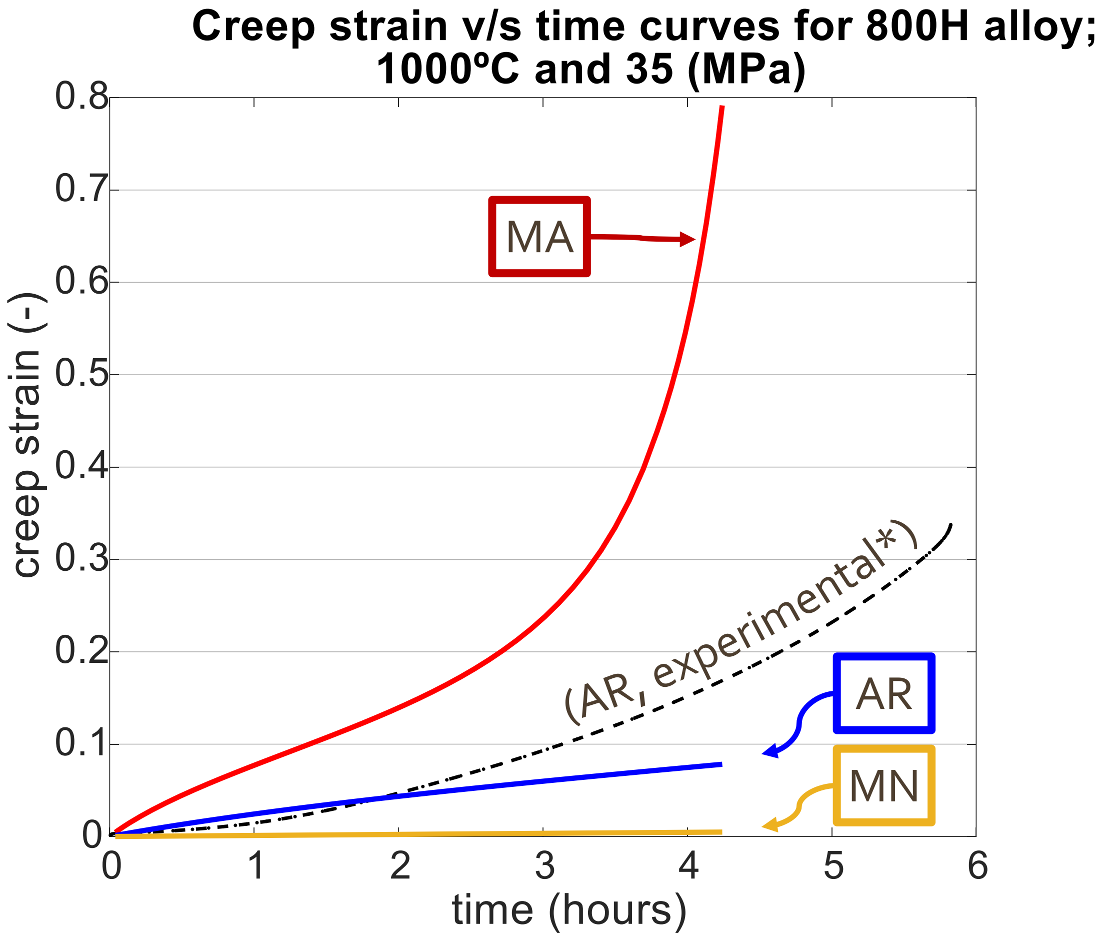


- Temperature
- N-concentration

Experiment for identification (A.M. Young et al., 2023):

Parameters		Aged (MA)	As-received (AR)	Nitrided (MN)
Norton law $\dot{p} = \left\langle \frac{\sigma_v}{K} \right\rangle^{n}$	k (MPa)	3.10E + 04	7.50E + 04	5.35E + 05
	n (—)	1.18	1.22	1.29

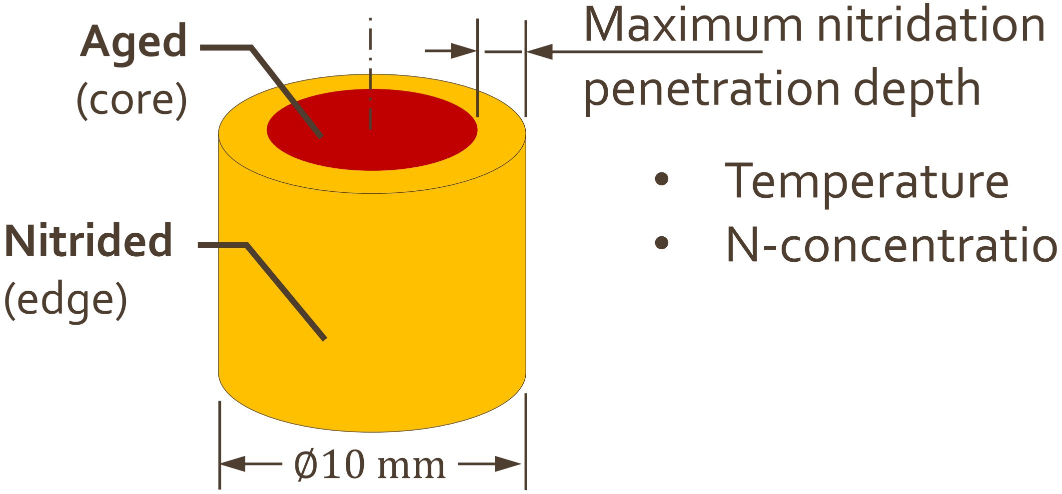
Prediction for homogeneous samples (Norton)


Creep strain v/s time curves for 800H alloy; 1000ºC and 35 (MPa)

*: Experimental curve after (V. Gutmann & R. Bürgel, 1983)

Environmental effects on creep: nitridation

FE simulation of nitridation effect (Lagamine code Uliege)

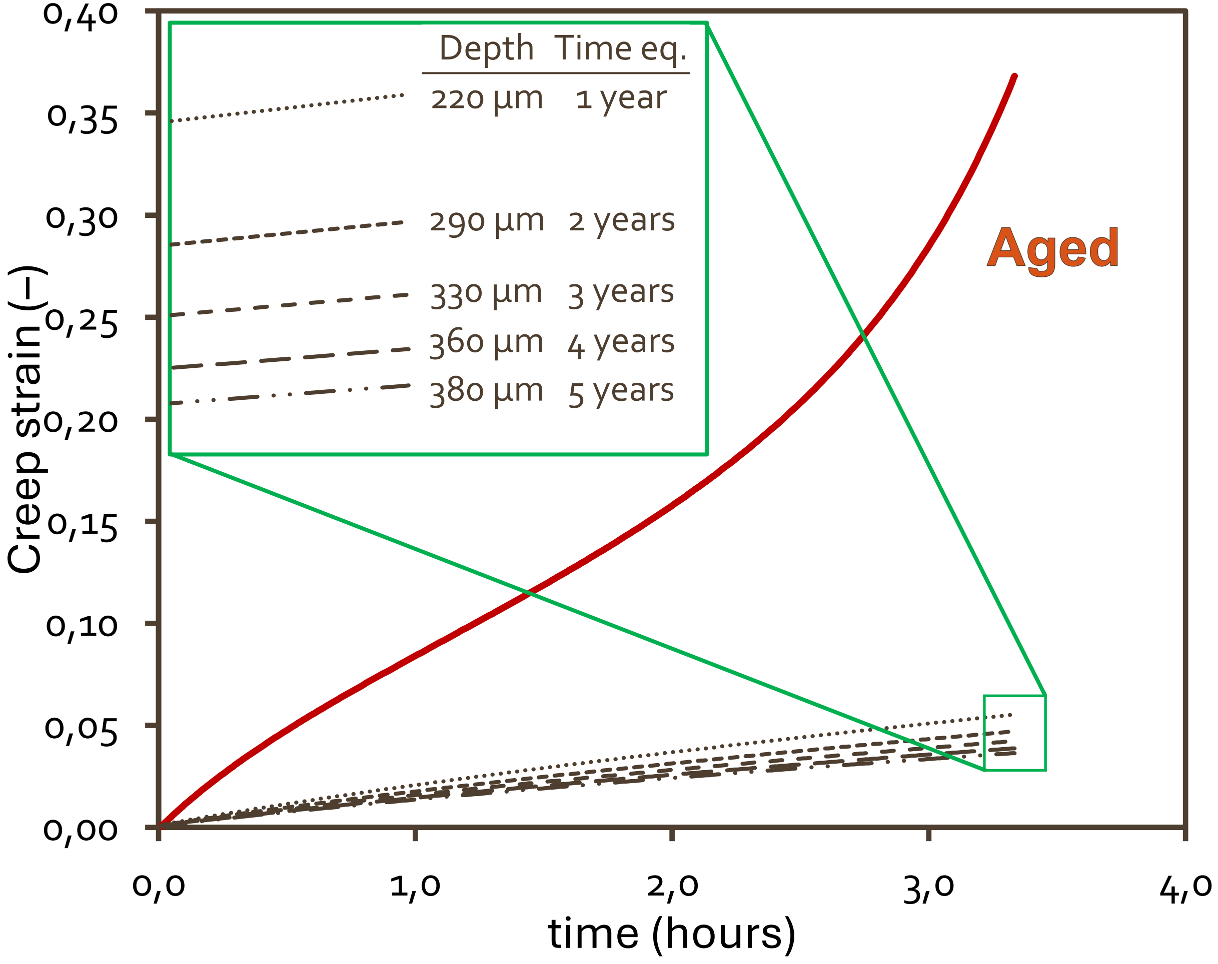


- Temperature
- N-concentration

Using the information from (A.M. Young et al., 2023):

Parameters		**Aged (MA)**	**As-received (AR)**	**Nitrided (MN)**
Norton law $\dot{p} = \left\langle \frac{\sigma_v}{K} \right\rangle^{n}$	k (MPa)	3.10E + 04	7.50E + 04	5.35E + 05
	n (—)	1.18	1.22	1.29

Predictions for different aged + nitrided 800H material combinations | 1000°C & 35 MPa



Contents

AID4Greenest project WP3 30CrMoNiV5-11 (≈ 1 % Cr)

- Manufacturing of a shaft *Reinosa*

- Characterization and prediction of microstructure *Uliege, Oulu, Fraunhofer, MDEA*
- Standard creep test *ULiege*
- 2 Types of Accelerated creep test *IMDEA - Fraunhofer*

- Forging + Cooling simulation *OULO*

- Creep Simulation: Macro laws (Morch) *Uliege*

  Micro law (under development) *Uliege*

  Machine learning (under development) *Fraunofer IMDEA*

Efficient way to predict shat lifetime

→ Generic tool development

https://aid4greenest.eu/

AID4GREENEST Official

Thank you for your attention

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