European Commission funded International Workshop
"Materials resistant to extreme conditions for future energy systems"
12-14 June 2017, Kyiv - Ukraine

# Cyclic viscoplasticity modelling of high temperature fatigue for 9Cr ferritic-martensitic steels

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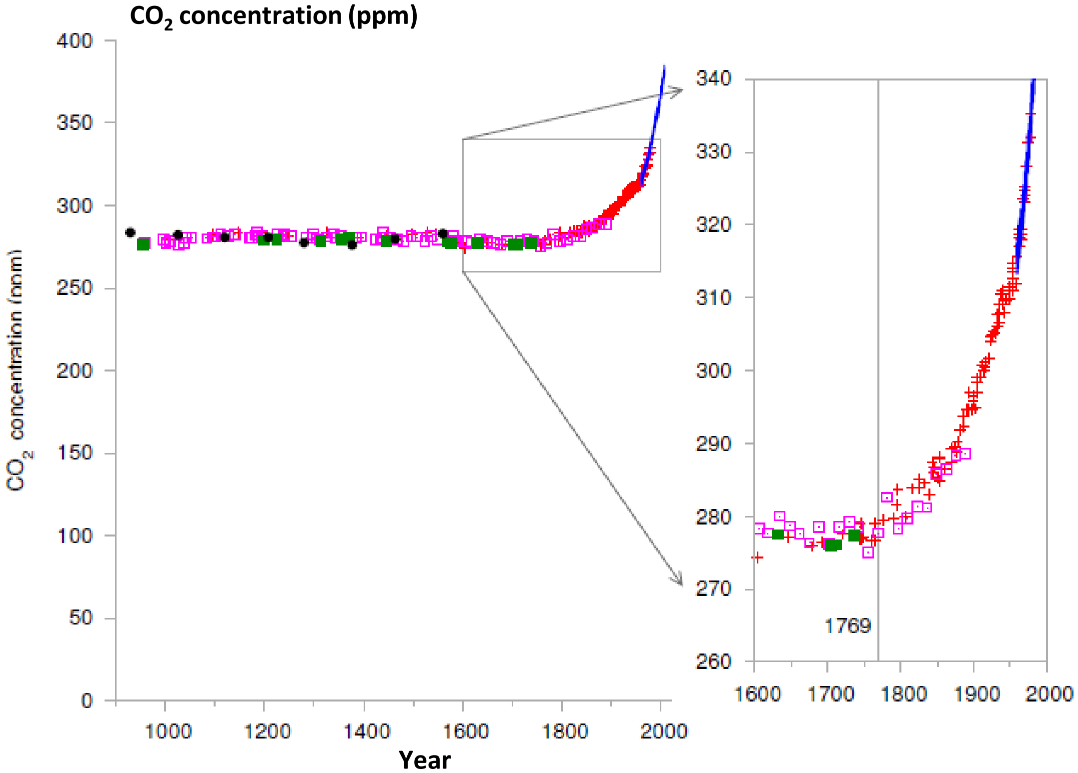
Science Foundation Ireland

# Agenda

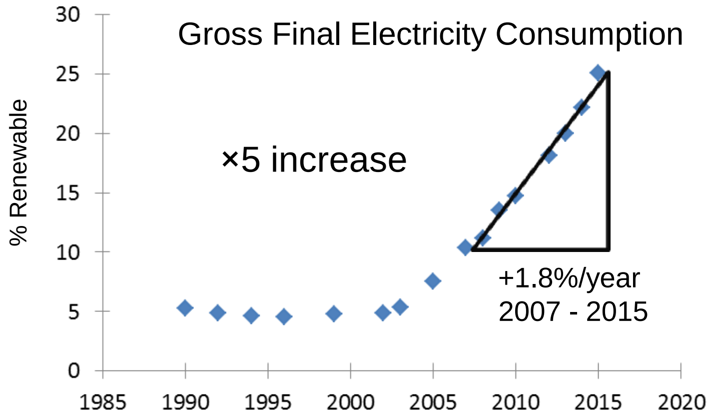
- Background and context
- Materials and testing:
  - High-temperature, low-cycle fatigue (HTLCF) and thermo-mechanical fatigue (TMF)
- Modelling
  - Unified cyclic viscoplasticity, crystal plasticity (CP), physically-based
- Conclusions and perspectives

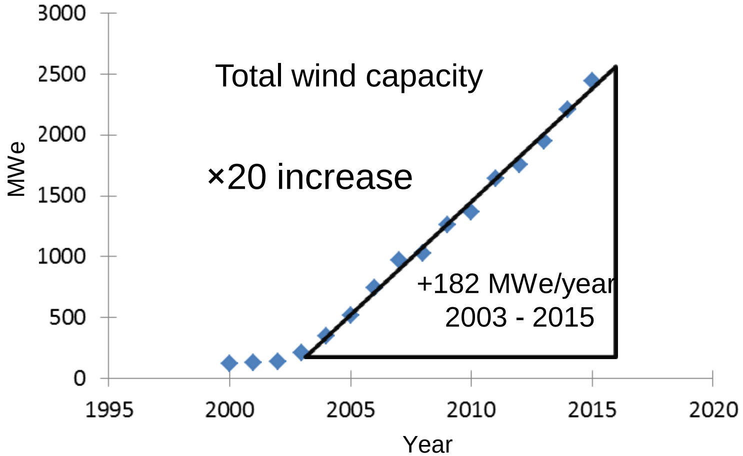
# $CO_2$ emissions




**David J.C. MacKay. Sustainable Energy – without the hot air.**
UIT Cambridge, 2008.

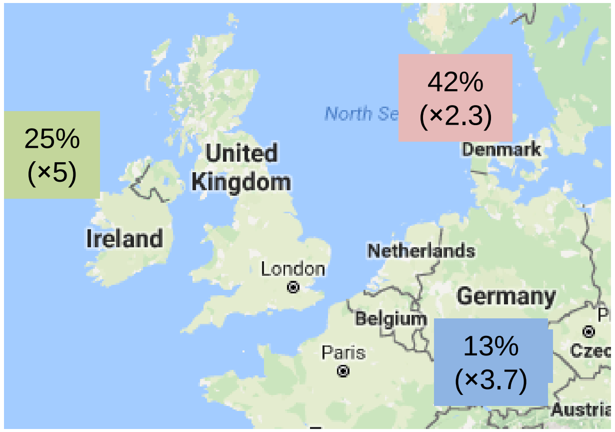
# The rise of wind energy




SEAI – 'Energy in Ireland 1990 – 2015', 2016 Report

2016




*M. G. Salameh, Applied Energy (2003)*

*WindEurope.org*

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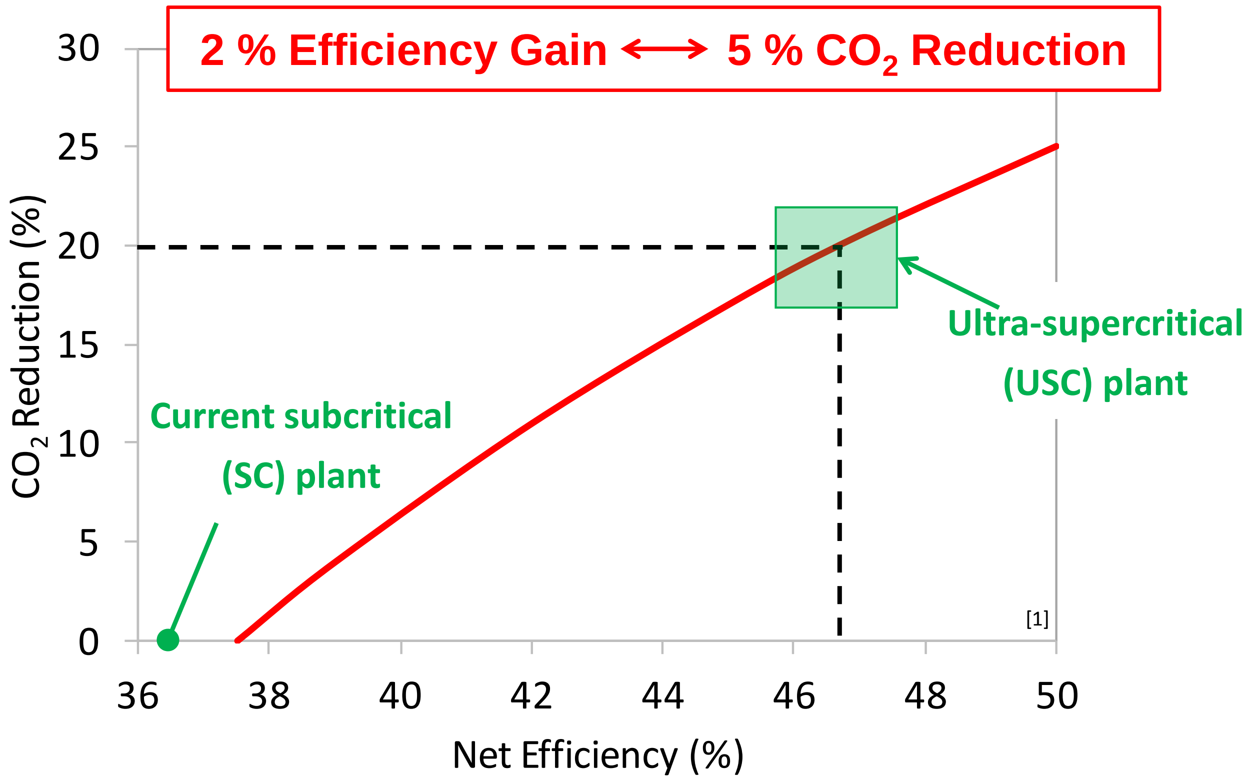
# Clean, efficient, sustainable energy




*Adapted from: Abson and Rothwell, Int. Materials Reviews, **58** (2013) 437-473*

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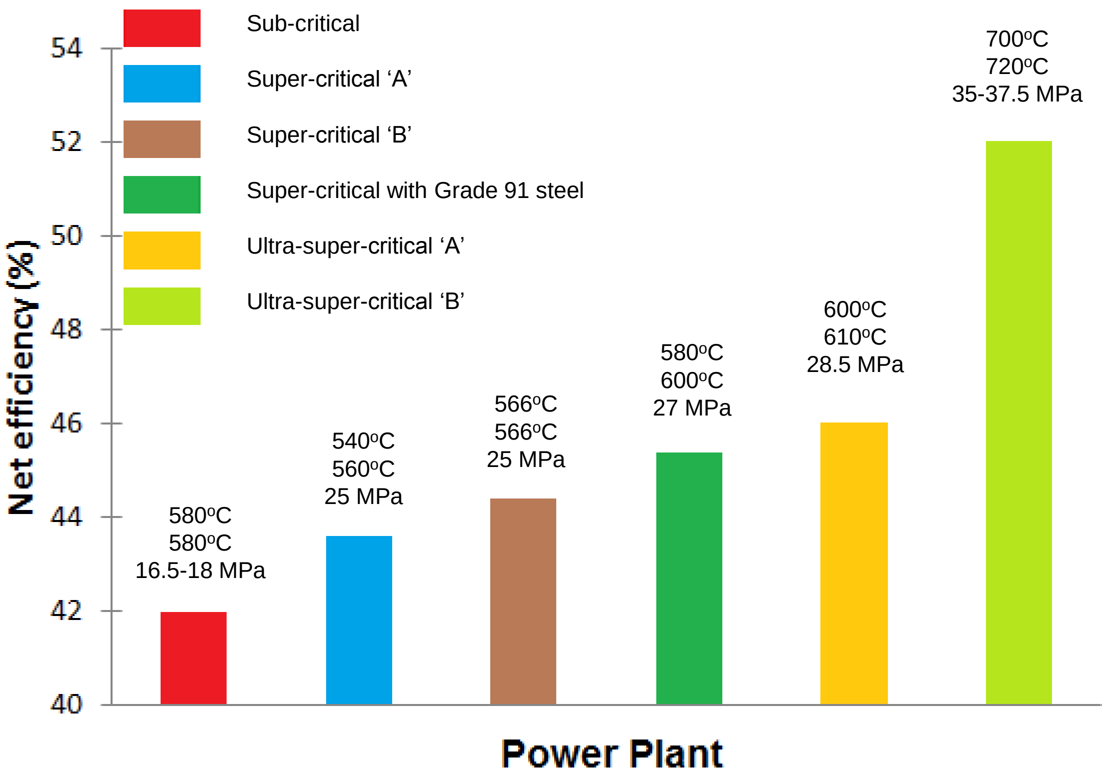
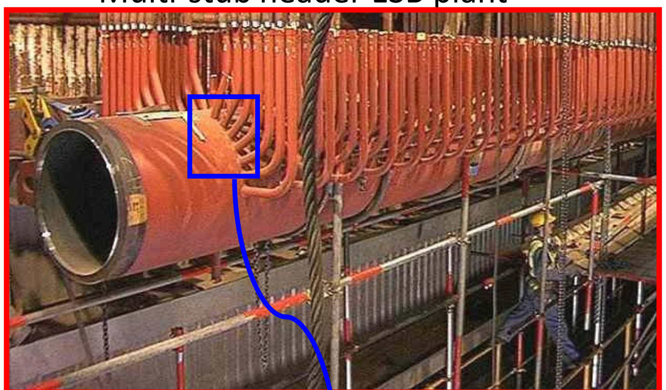
# Ultra-super critical power generation

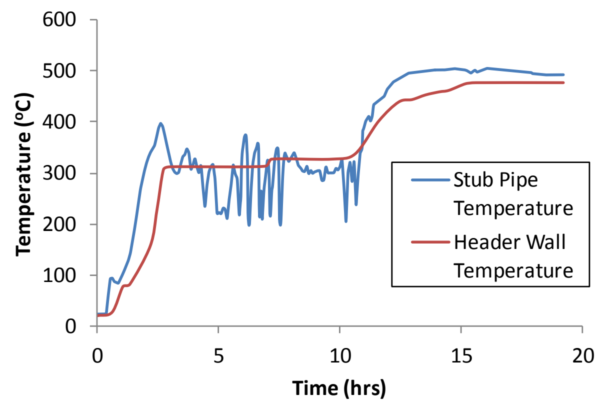



**Potirniche, G, U. of Idaho,**
Nuclear Energy University Programs, 2013

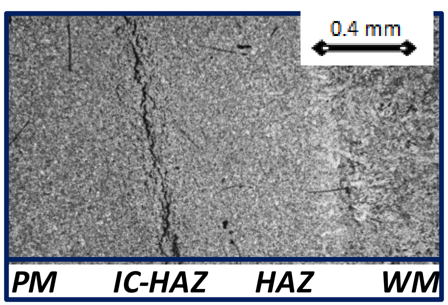
# Cyclic degradation of power plant

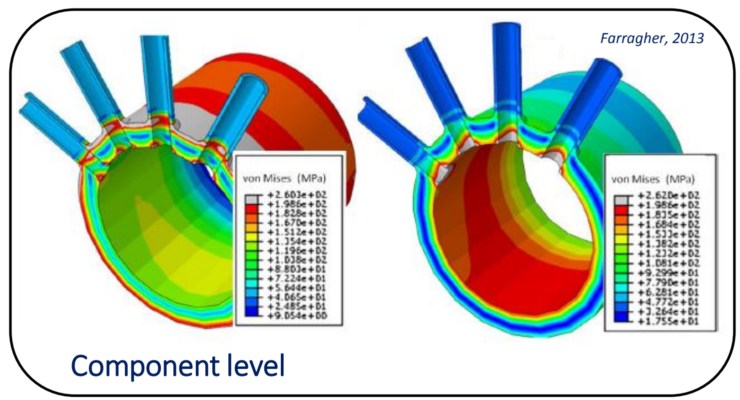
Multi-stub header ESB plant






ICHAZ cracking in a P91 T-piece




**TMF-accelerated microstructural degradation and crack formation due to increased flexible operation.**

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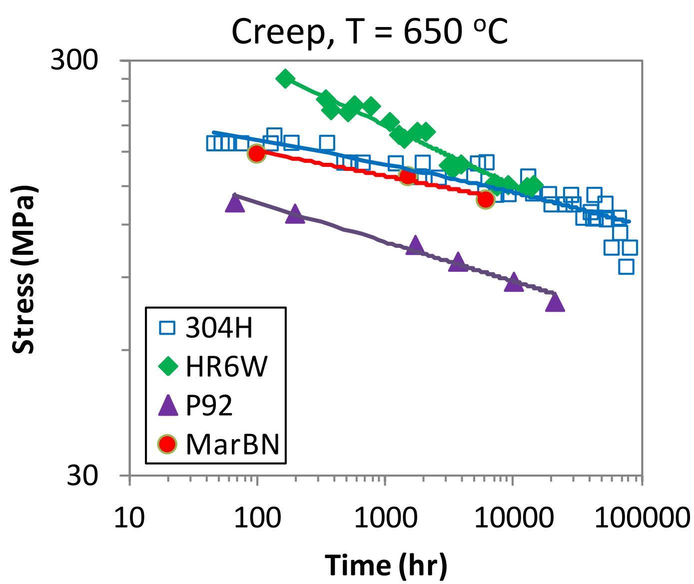
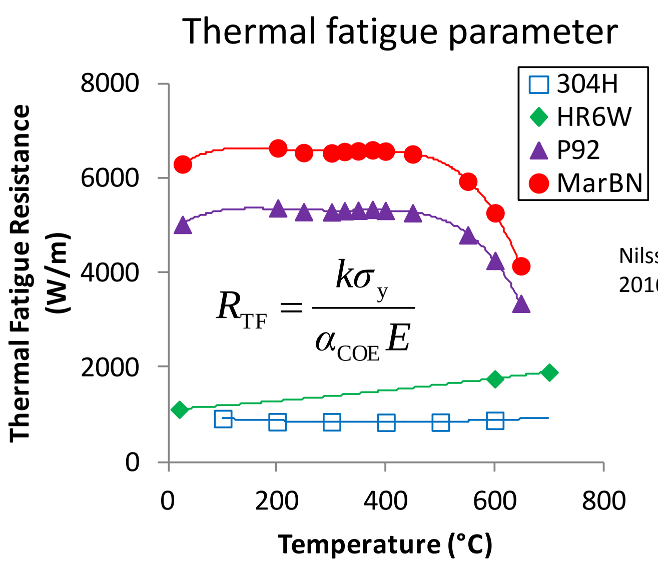
# Next generation power plant materials




Nilsson et al., *Eng Fract Mechs*, 2016.

| | Al | B | C | Co | Cr | Mn | Mo | N | Nb | P | Si | V | W |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **P91** | 0.007 | - | 0.10 | - | 8.48 | 0.42 | 0.94 | 0.058 | 0.07 | 0.013 | 0.26 | 0.204 | - |
| **MarBN** | - | 0.018 | 0.081 | 3.10 | 9.08 | 0.51 | - | 0.065 | 0.055 | - | 0.31 | 0.2 | 3.13 |

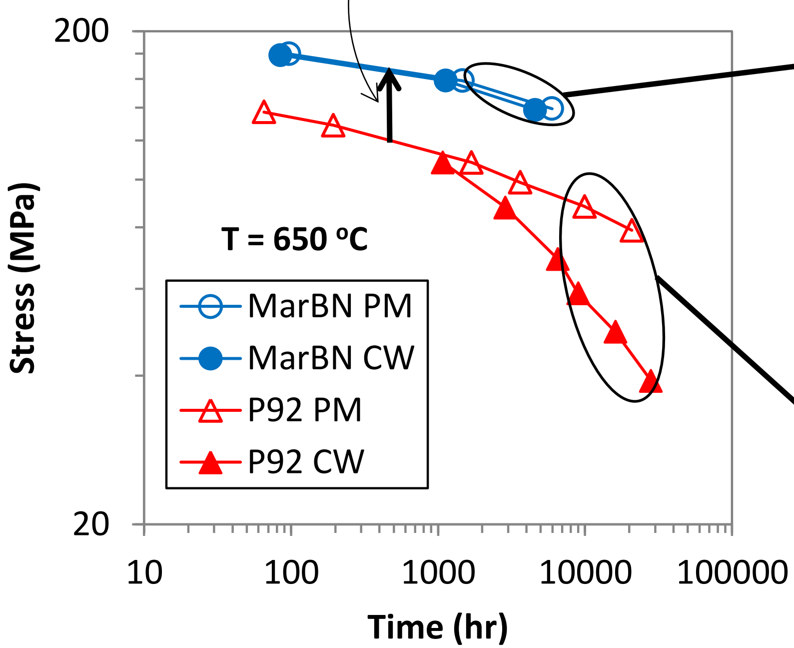
*MarBN composition: Abe et al., 2008*

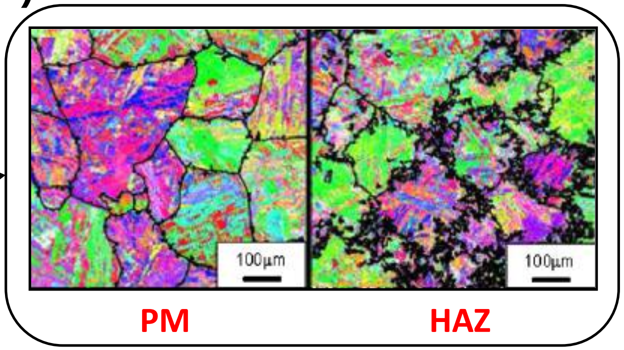
# Need for higher temperature materials

**Higher temperature operation (~650 $^{o}$C).**

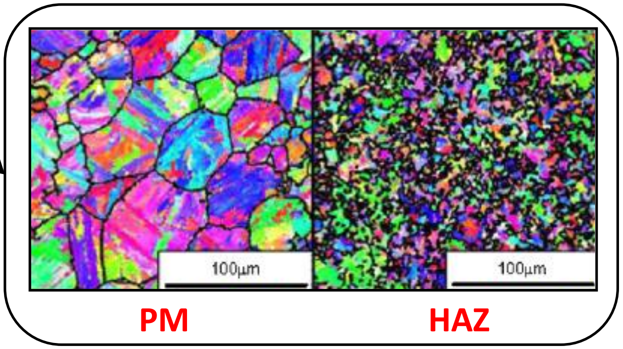
**Enhanced creep performance compared with P92 steel**

Abe et al., *Int. J. PVP* (2007), *Adv. in Matls. Tech. for Fossil Power Plants* (2007).




***Suppression of Type IV failure***




***Fatigue behaviour of MarBN…***

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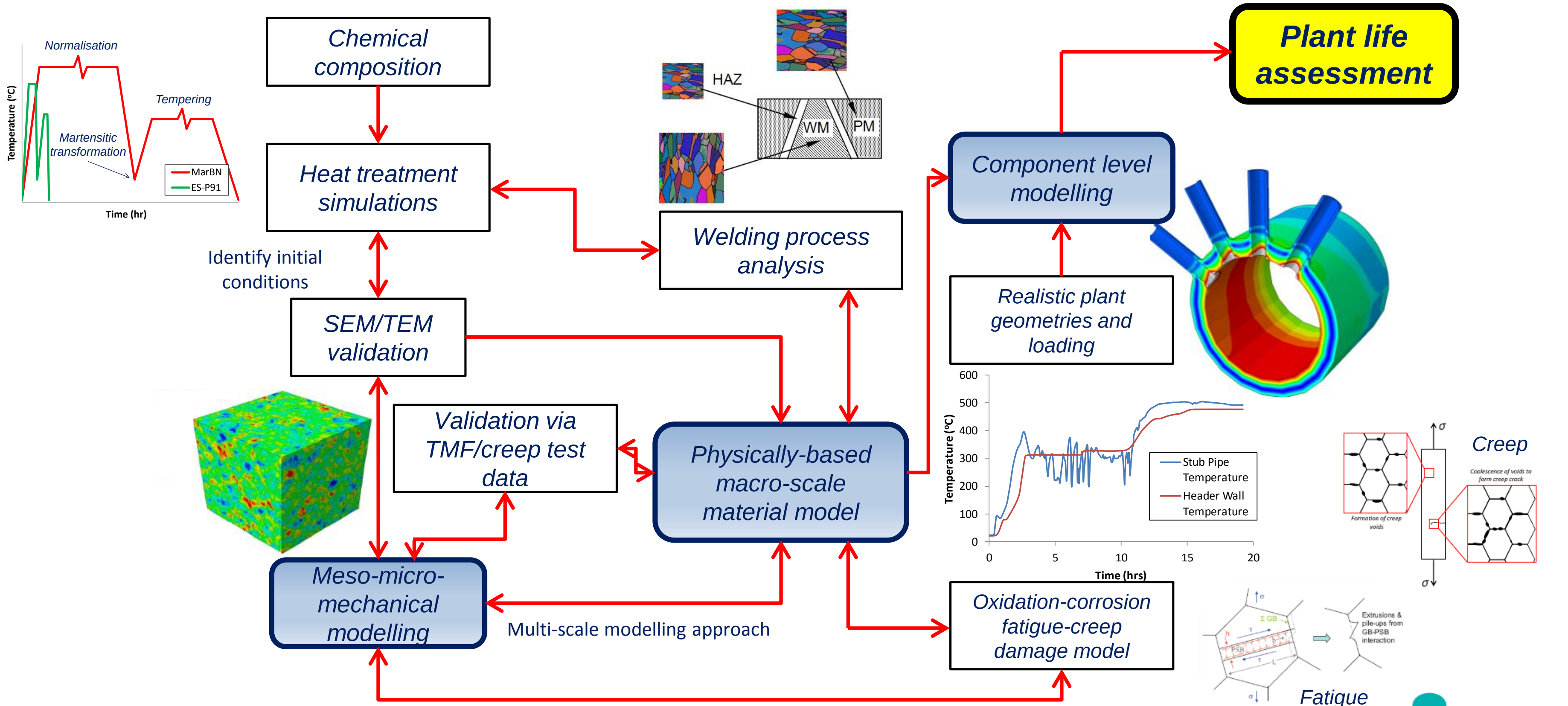
# A through-process materials design tool for welds

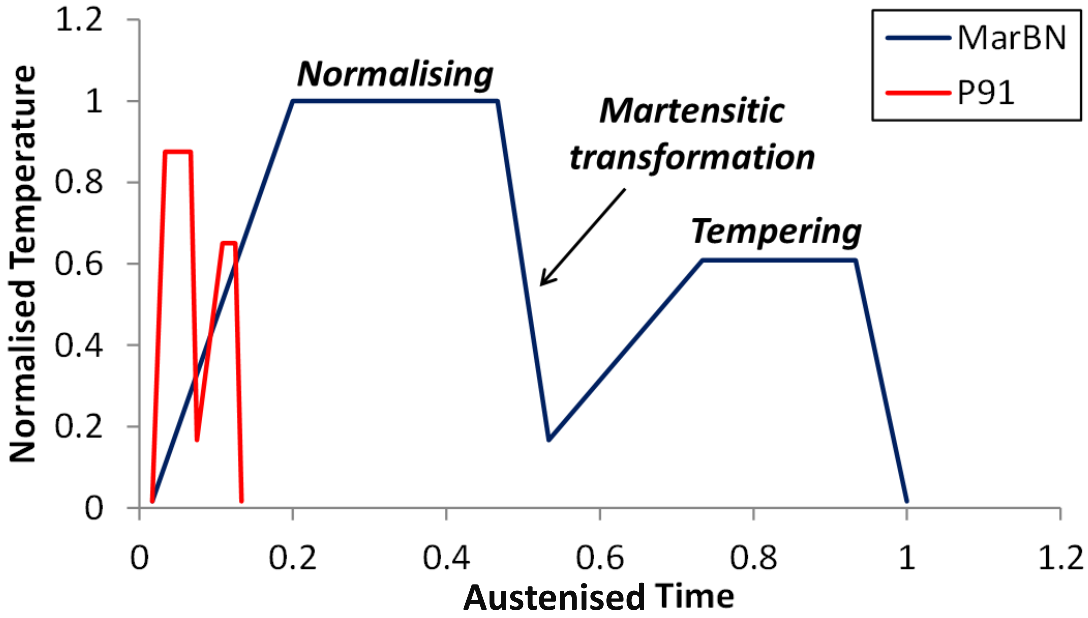


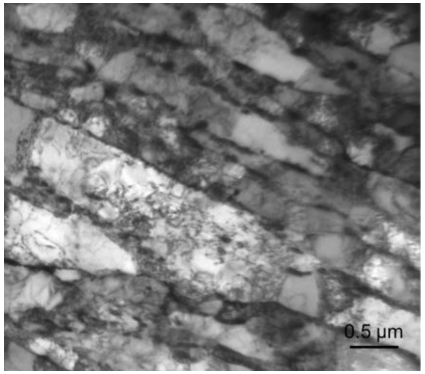

Adapted from R Barrett, PhD Thesis, NUI Galway, 2016

# Heat treatment of MarBN and P91

**Normalising:**
- Coarser microstructure
- Less regions for creep voids to form

**Tempering:**
- $M_{23}C_6$ and MX precipitates form
- Coarser martensitic lath width
- Reduced precipitate spacing




In conjunction with Dr. Yina Guo of University of Limerick. IMPEL Consortium.

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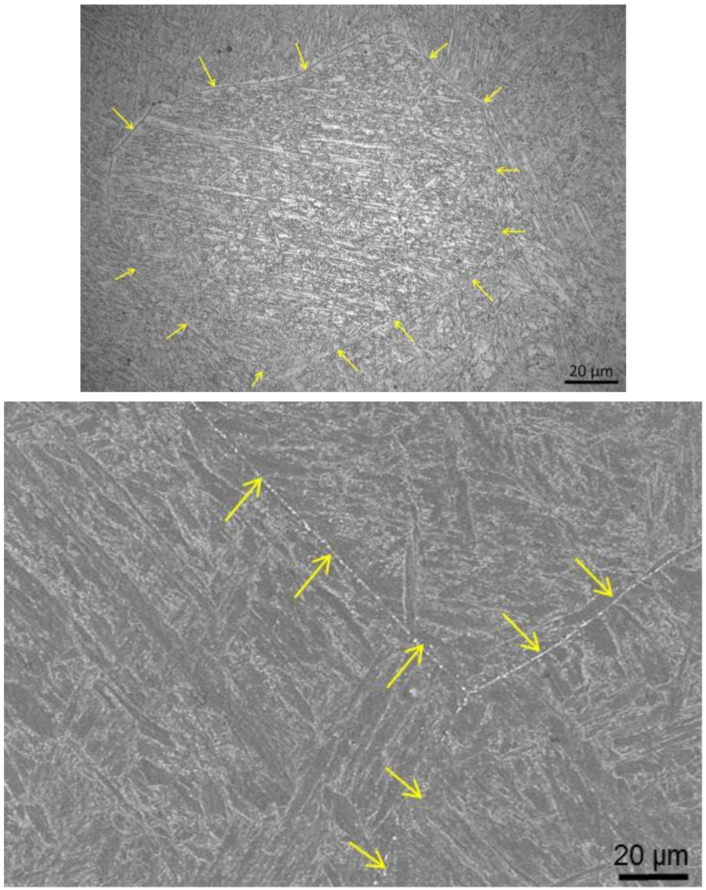
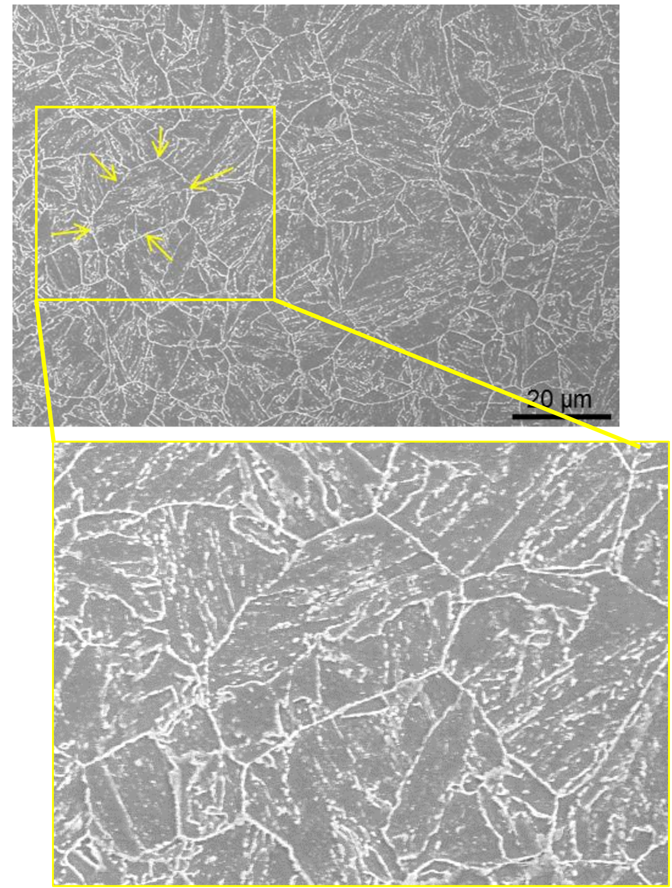
# SEM of MarBN and P91



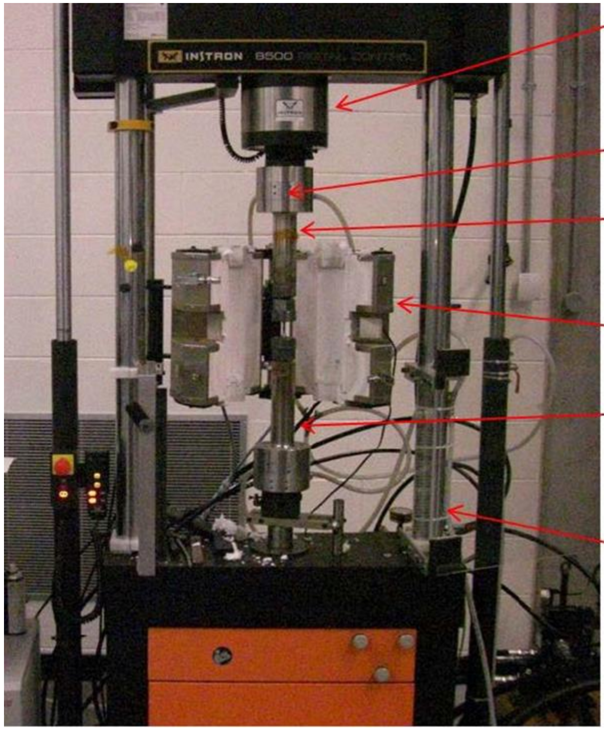

Cast MarBN




P91

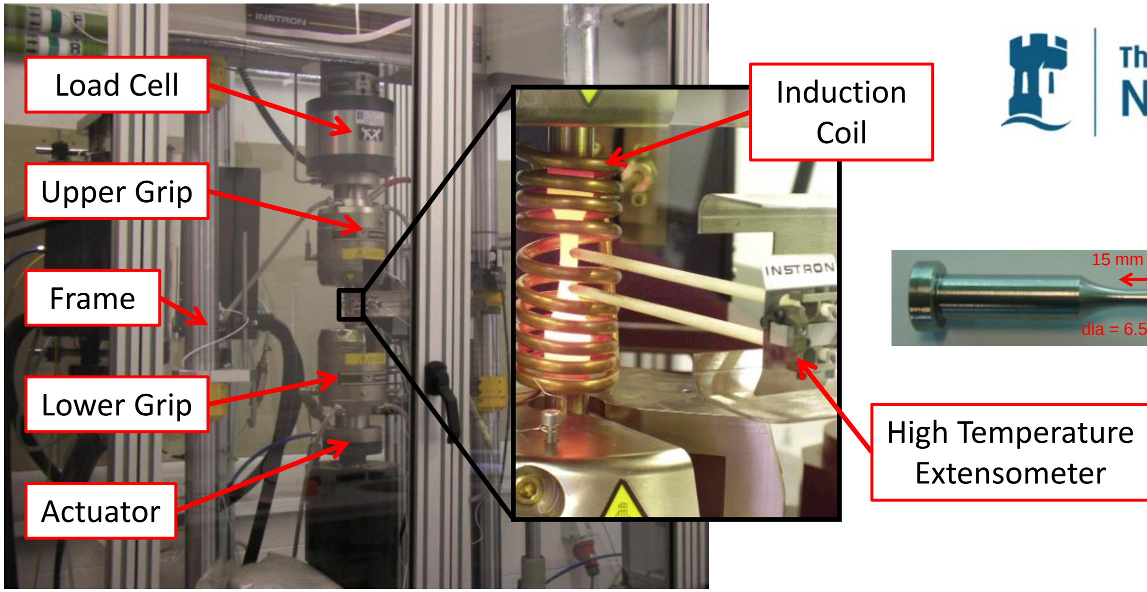
# HTLCF Testing

- Strain-controlled cyclic testing
  - Stress-control
- Water cooled hydraulic pull-rods
- Servo-electric actuator
- Furnace with maximum temperature of 1000 °C
- High temperature axial gauge extensometer
- FT Console and LCF3 software for HTLCF testing

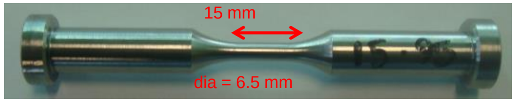


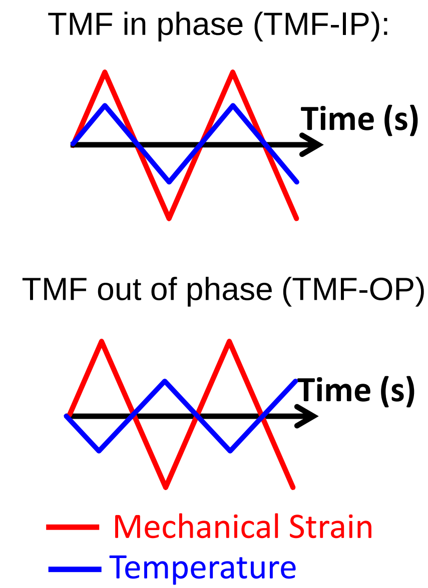

| *Test Type* | *Strain-range (%)* | *Strain-rate (%/s)* | *Waveform* |
|---|---|---|---|
| HTLCF 650 °C | ±0.5 | 0.1, 0.01 | $R_\varepsilon = -1$ (Triangular) |
| HTLCF 600 °C | ±0.5 | 0.1, 0.0333, 0.01 | $R_\varepsilon = -1$ (Triangular) |
| | ±0.4 | 0.033, 0.01 | |
| | ±0.3 | 0.033, 0.01 | |
| Cyclic Dwell 600 °C | ±0.5 | 0.1 | 1 hour hold period |

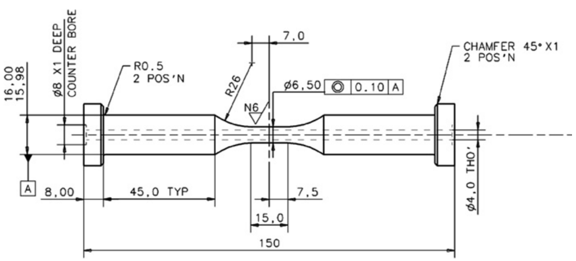
# TMF Testing




The University of Nottingham




| Temperature (°C) | Strain Rate (%/s) | Strain Range (±%) | Wave time (s) | Heating/ Cooling rate (°C/s) | Waveform | Phase | Test Type | Specimen Type | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 400-600 | 0.01 | 0.5 | 320 | 2 | $R_\varepsilon$= -1 Triangular | In-phase | Anisothermal | Hollow | 2 min Hold |
| | 0.01 | 0.5 | 320 | 2 | $R_\varepsilon$= -1 Triangular | Out-of-phase | Anisothermal | Hollow | 2 min Hold |
| | 0.0333333 | 0.5 | 180.00006 | 6.66666 | $R_\varepsilon$= -1 Triangular | In-phase | Anisothermal | Hollow | 2 min Hold |
| | 0.0333333 | 0.5 | 180.00006 | 6.66666 | $R_\varepsilon$= -1 Triangular | Out-of-phase | Anisothermal | Hollow | 2 min Hold |
| | 0.025 | 0.5 | 200 | 5 | $R_\varepsilon$= -1 Triangular | In-phase | Anisothermal | Hollow | 2 min Hold |
| | 0.025 | 0.5 | 200 | 5 | $R_\varepsilon$= -1 Triangular | Out-of-phase | Anisothermal | Hollow | 2 min Hold |

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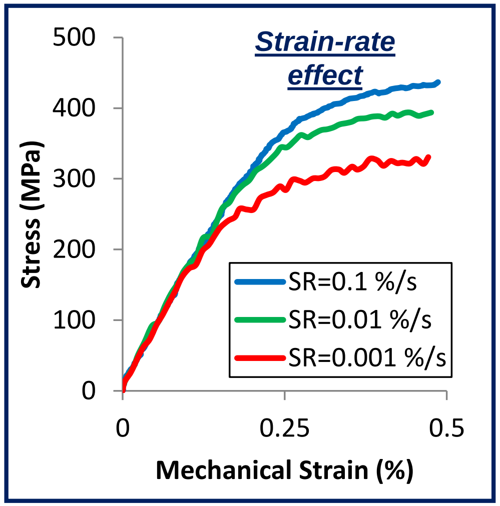
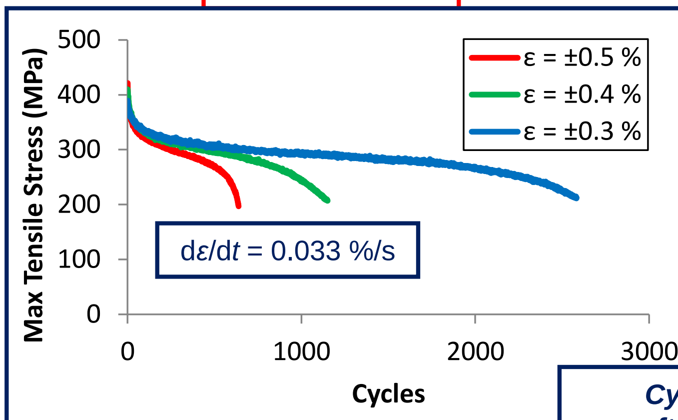
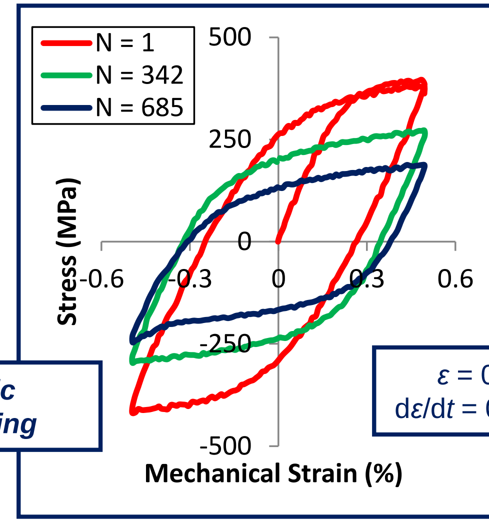
# HTLCF Test Results: MarBN

*T = 600 °C*



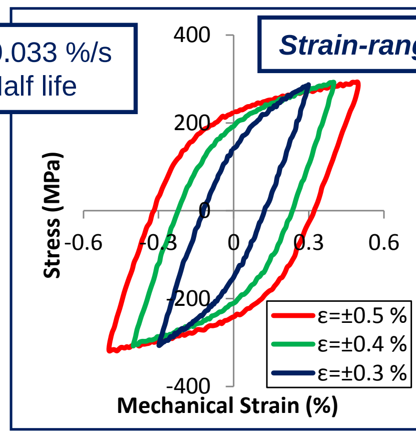




*Cyclic softening*




dε/dt = 0.033 %/s
*N* = Half life

*Strain-range response*

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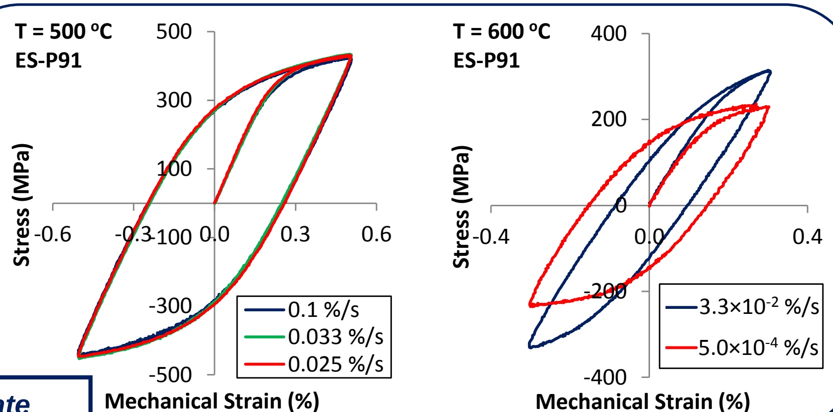
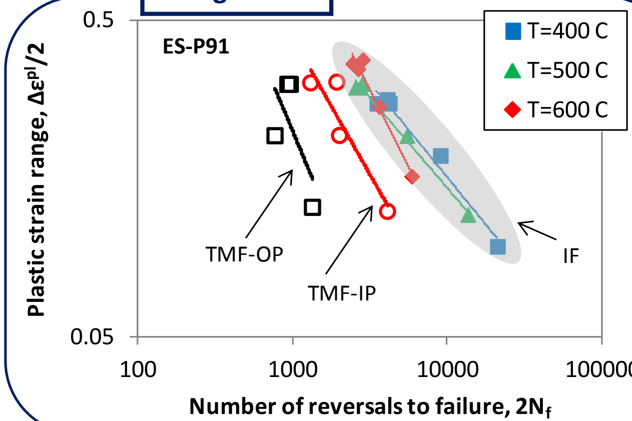
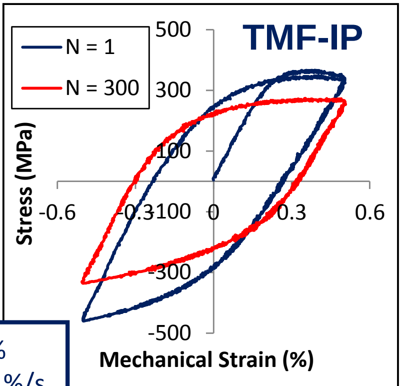
# HTLCF and TMF results: ex-service P91



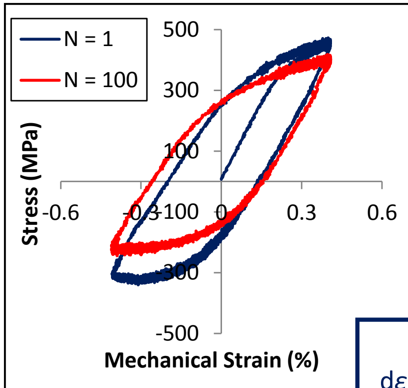

***Strain-rate effect***

***Fatigue life***



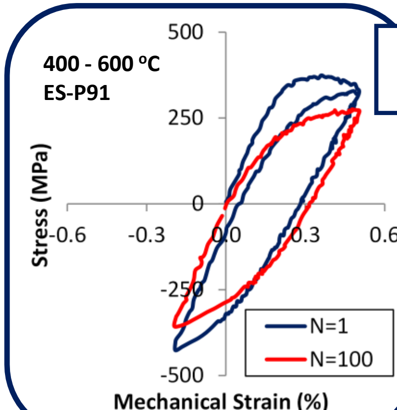

$\varepsilon = \pm 0.5$ %
$d\varepsilon/dt = 0.025$ %/s




**TMF-OP**

$\varepsilon = \pm 0.4$ %
$d\varepsilon/dt = 0.033$ %/s

***Representative TMF***

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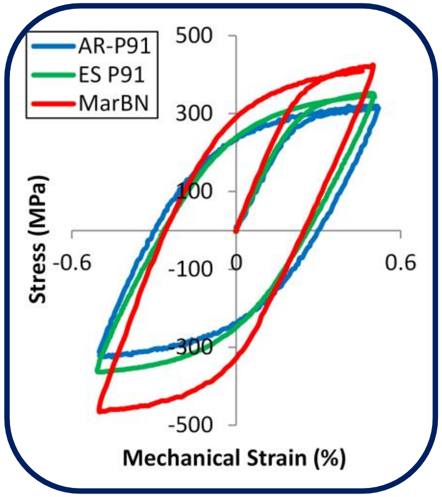
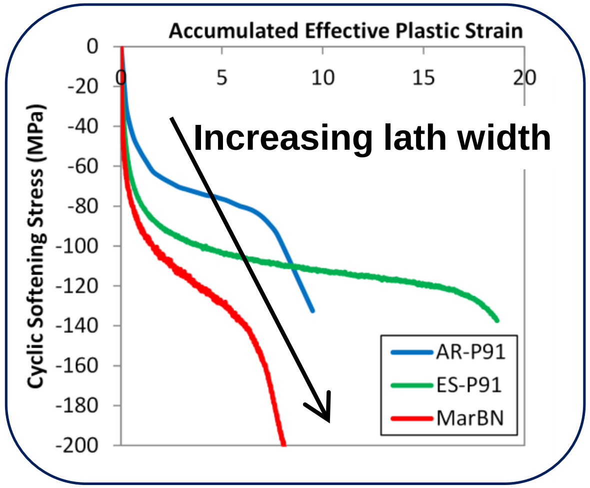
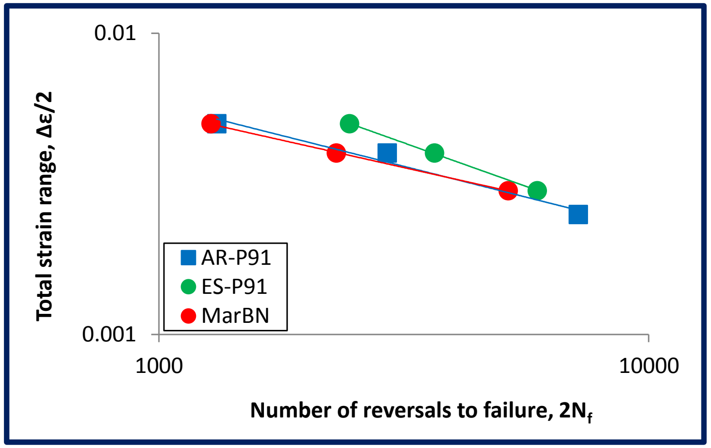
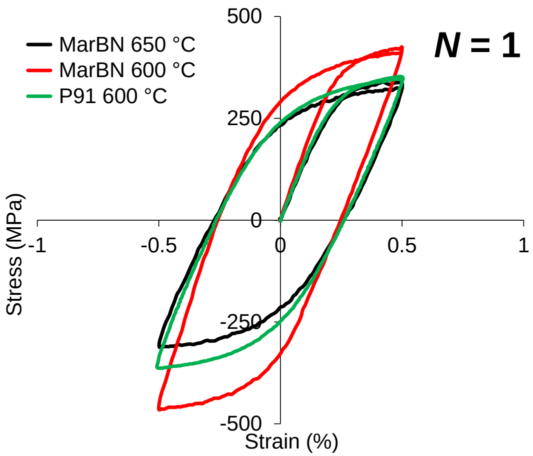
# Enhanced cyclic performance of MarBN

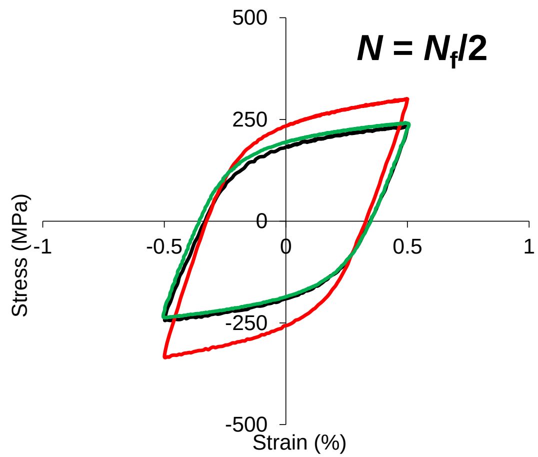


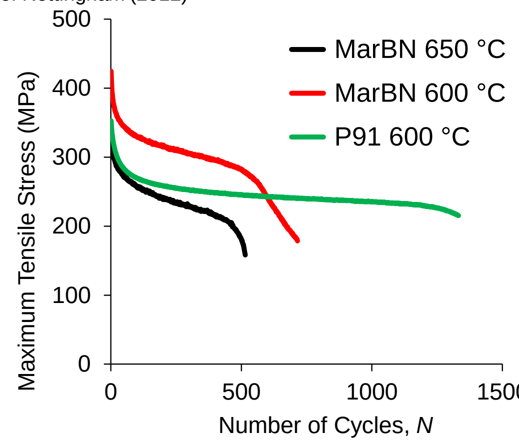




***AR-P91 data:*** Saad, PhD thesis, University of Nottingham (2012)

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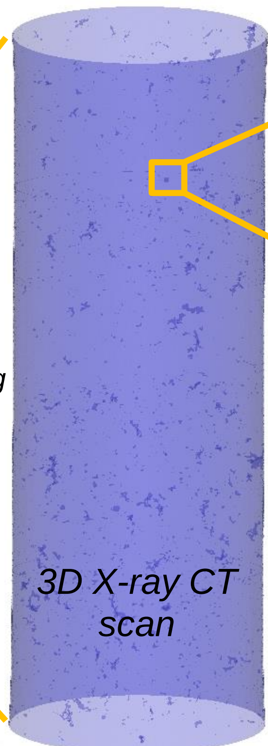
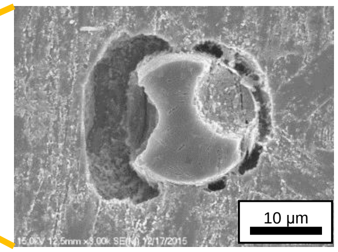
# Process-induced defects: MarBN fatigue

MarBN

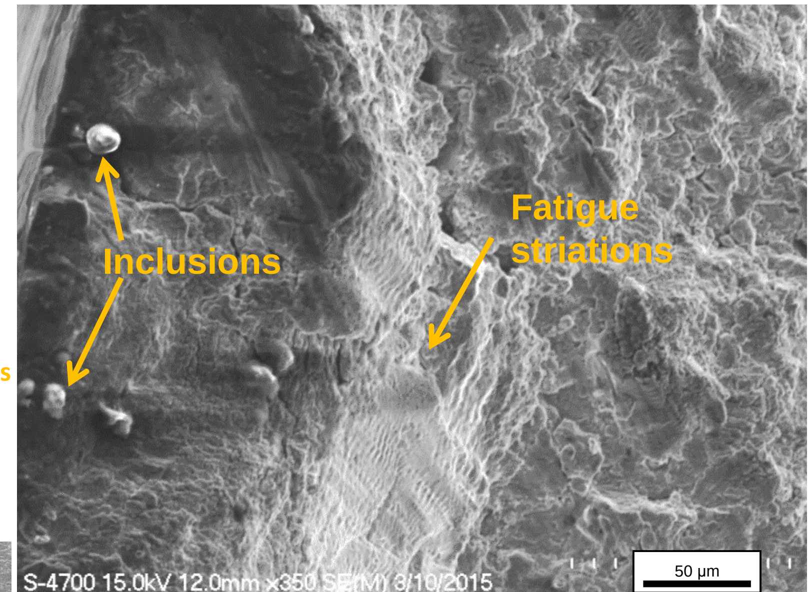
*High volume fraction of casting defects and inclusions*

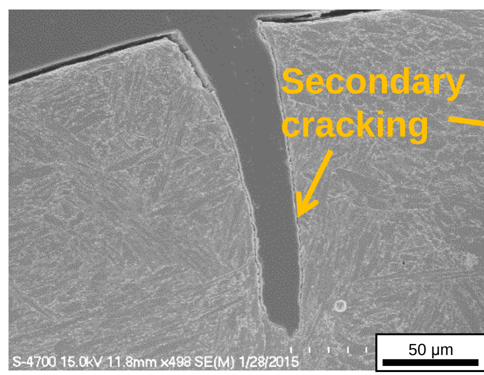


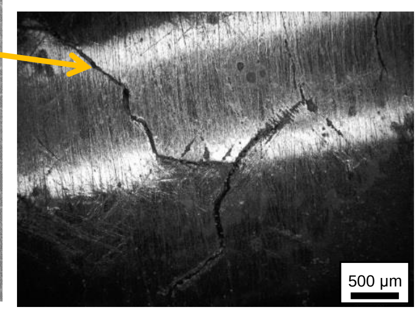

6.5 mm




Micro-crack initiation at inclusions

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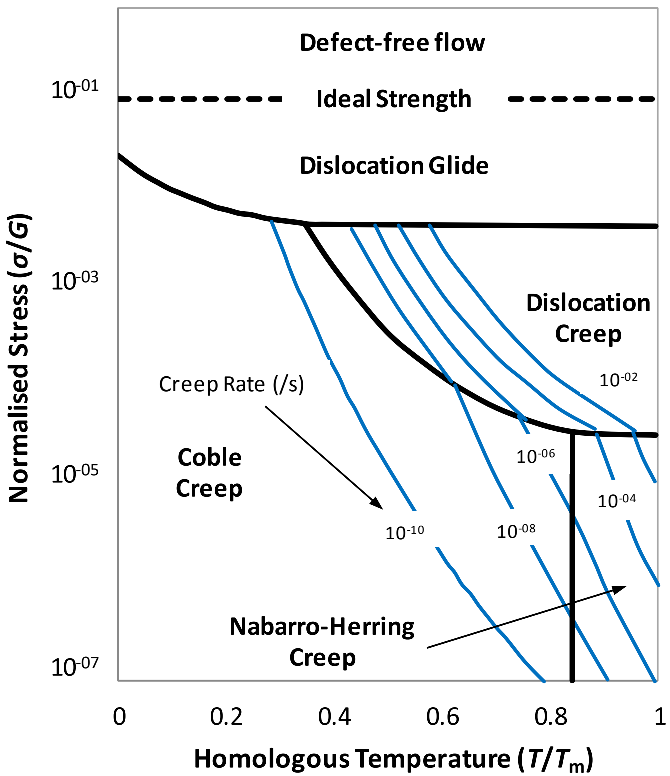
# Unified cyclic viscoplastic model: hyperbolic sine

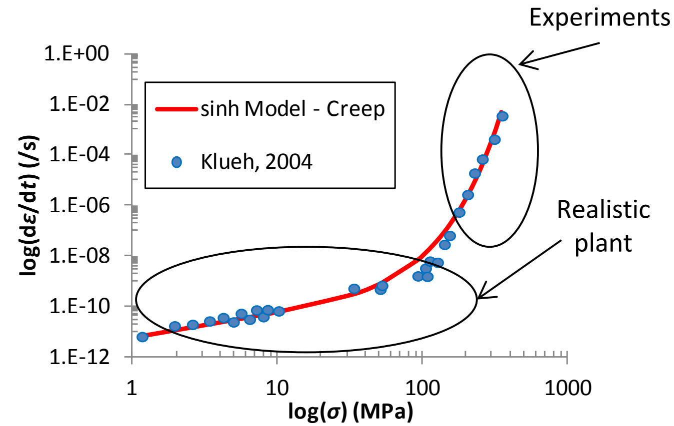



Low stress regime: ***Diffusion*** creep

High stress regime: ***Dislocation*** creep

***Hyperbolic sine*** model allows for varying creep exponent

$$\dot{\varepsilon}_{CR} = \alpha_{CR} \sinh(\beta_{CR}\sigma)$$

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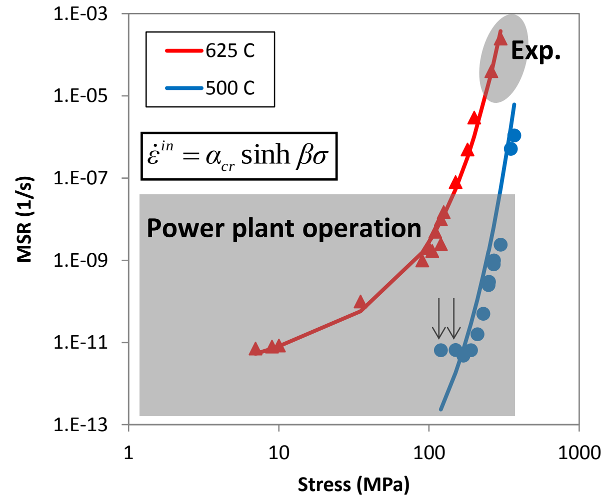
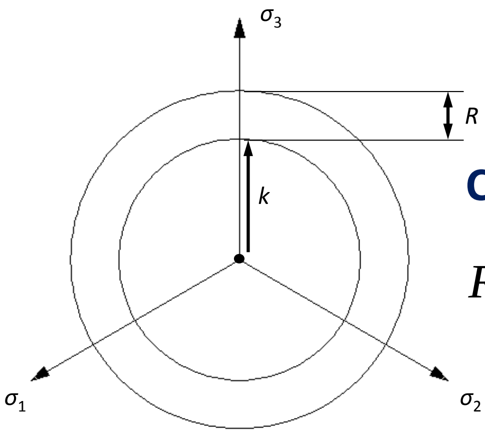
# Unified cyclic viscoplasticity model

**Flow rule:** $\dot{\boldsymbol{\varepsilon}}^{in} = \alpha \sinh(\beta f)\mathbf{n} = \dot{p}\mathbf{n}$

**'Yield' function:** $f = \mathrm{J}(\mathbf{s} - \mathbf{x}) - R - k$




Haney et al., 2009

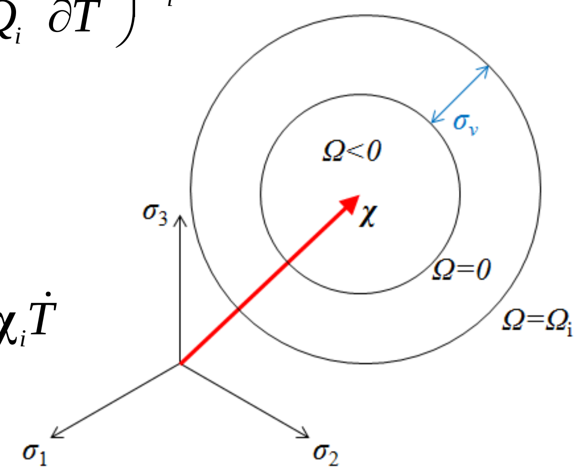



**Cyclic softening:**

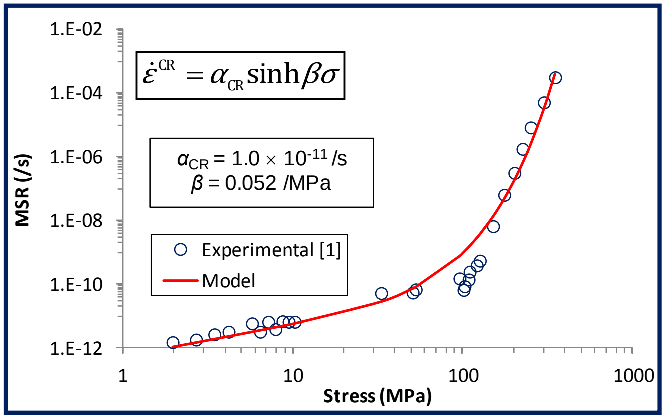
$$R = R_1 + R_2 \qquad \dot{R}_i = b_i(Q_i - R_i)\dot{p} + \left(\frac{1}{b_i}\frac{\partial b_i}{\partial T} + \frac{1}{Q_i}\frac{\partial Q_i}{\partial T}\right)R_i\dot{T}$$

**Kinematic back-stress:**

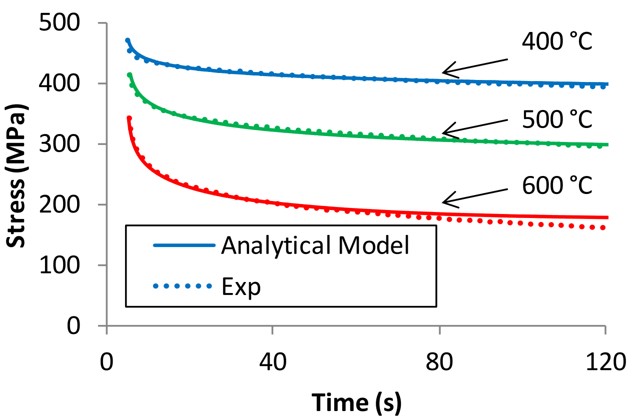
$$\boldsymbol{\chi} = \boldsymbol{\chi}_1 + \boldsymbol{\chi}_2 \qquad \dot{\boldsymbol{\chi}}_i = \frac{2}{3}C_i\dot{\boldsymbol{\varepsilon}}^{in} - \gamma_i\boldsymbol{\chi}_i\dot{p} + \frac{1}{C_i}\frac{\partial C_i}{\partial T}\boldsymbol{\chi}_i\dot{T}$$



# Parameter identification




1. *Sklenicka et al., (2003) Matls. Char.,* ***51****, 35-48.*




Elastic parameters, $E$, $k$ and $\nu$

↓

Determine $b_i$ and $Q_i$

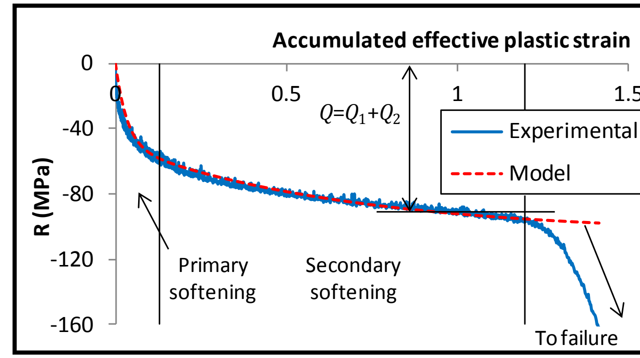
↓

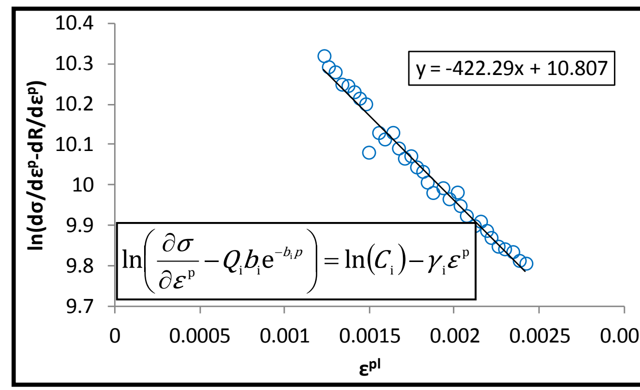
Identify $C_i$ and $\gamma_i$

↓

Correlate $\alpha$ and $\beta$ from analytical model

$$LS = \sum_{1}^{n} \left(\sigma^{\exp} - \sigma^{th}\right)^2$$

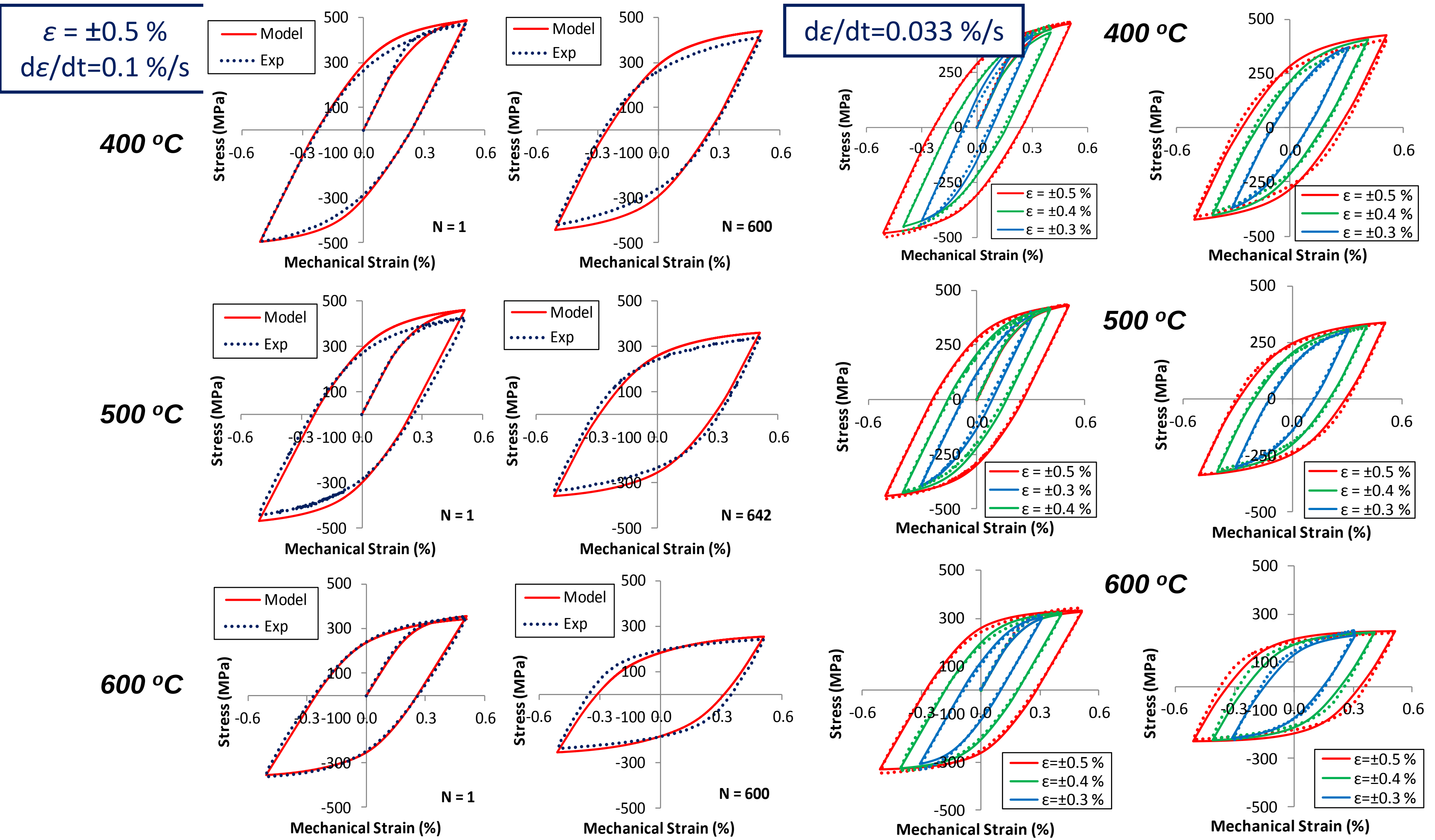



Analytical model for stress relaxation:

$$\sigma = \frac{2}{\beta}\tanh^{-1}\left(\tanh\left(\frac{\beta(\sigma_0 - \chi - k)}{2}\right)e^{-\alpha\beta E(t-t_0)}\right) + \chi + k$$

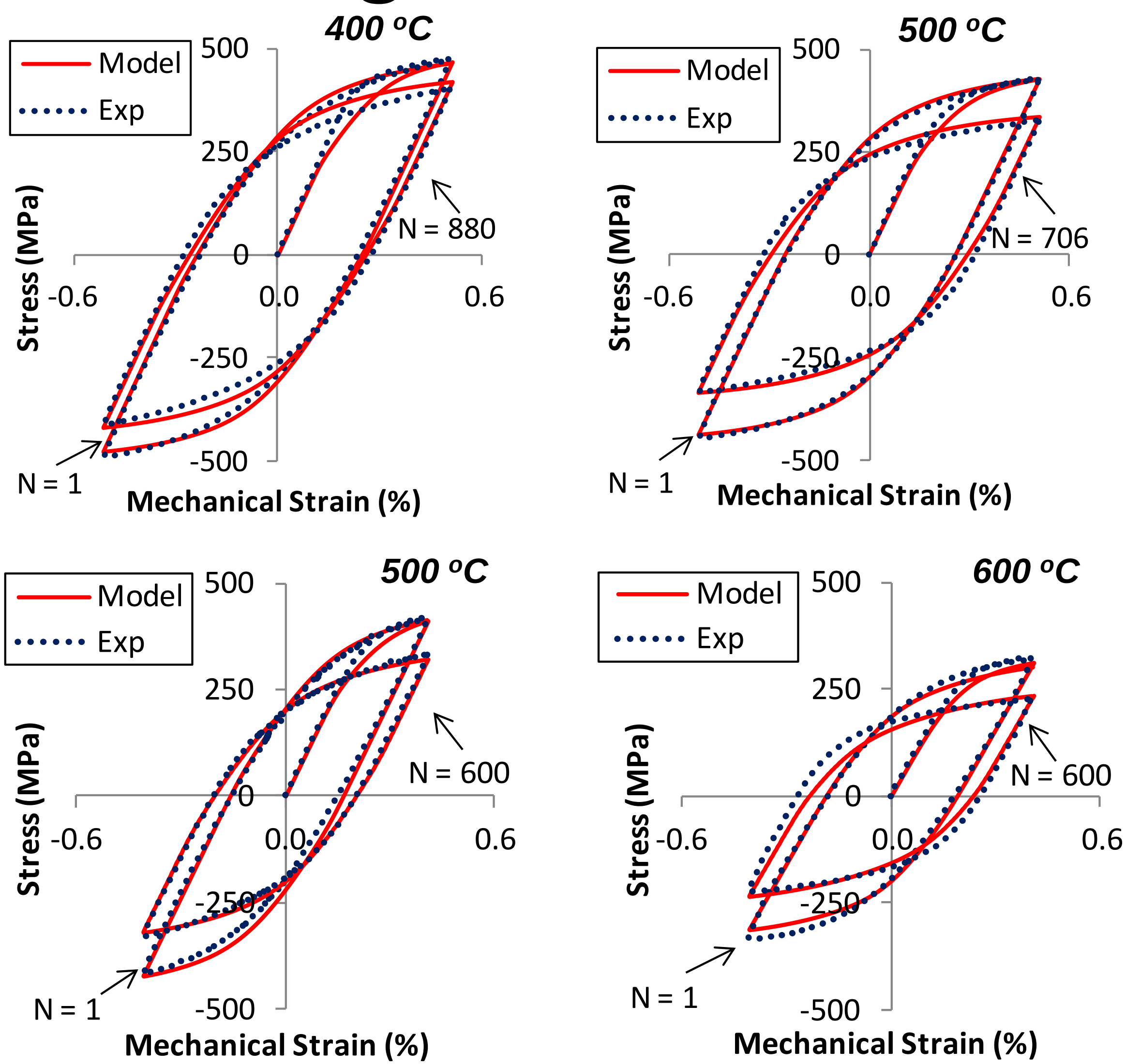
# Calibration and validation: P91



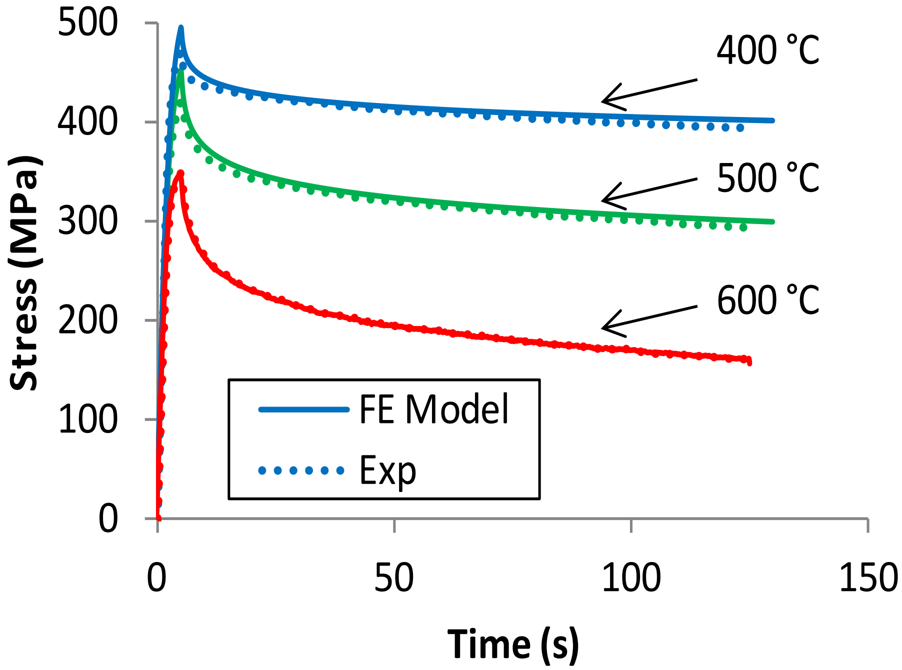
# Softening effect: P91

$\varepsilon = \pm 0.5$ %
$d\varepsilon/dt = 0.25$ %/s

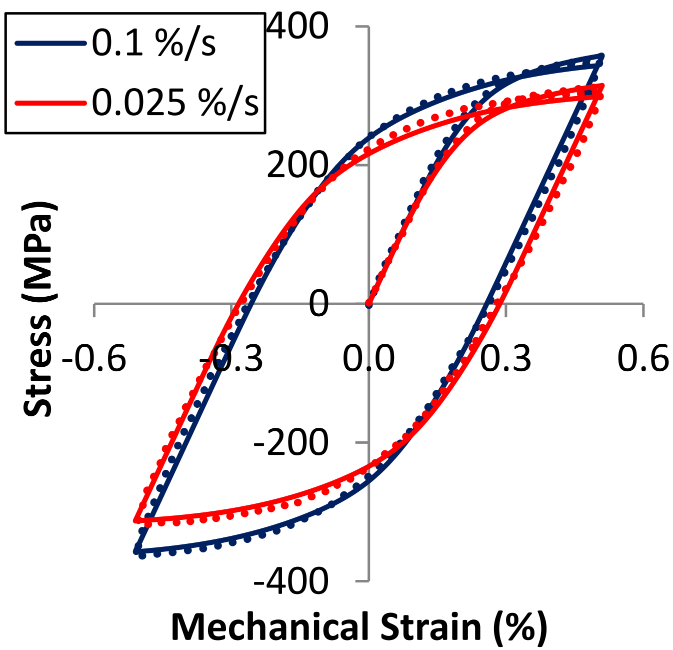
$\varepsilon = \pm 0.4$ %
$d\varepsilon/dt = 0.033$ %/s



# Strain-rate effect: P91



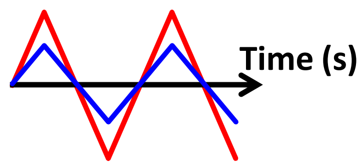

600 °C

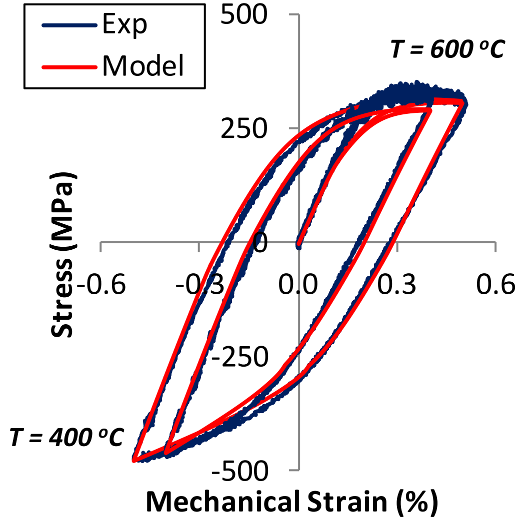


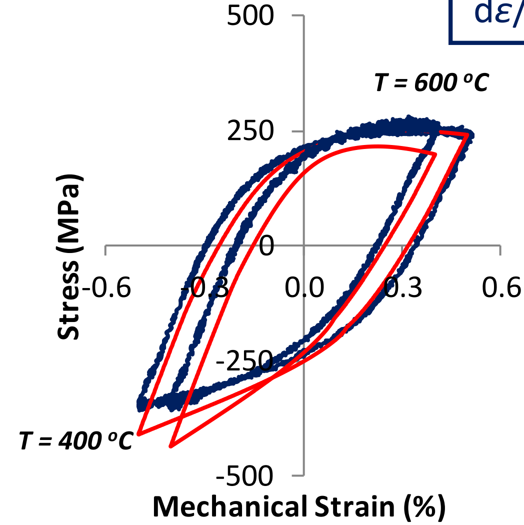
# TMF modelling: P91

dε/dt=0.033 %/s

TMF-IP

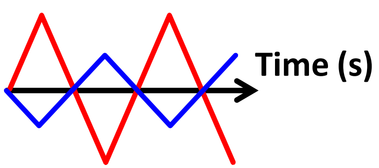


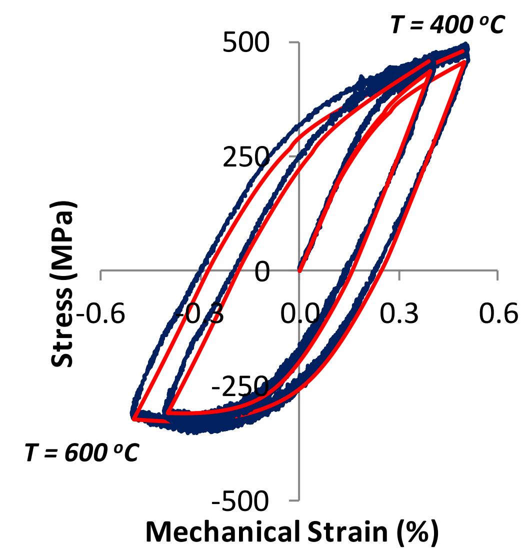



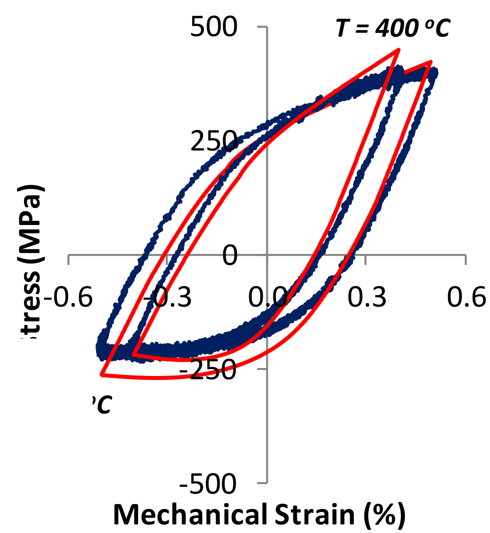




Mechanical Strain
Temperature

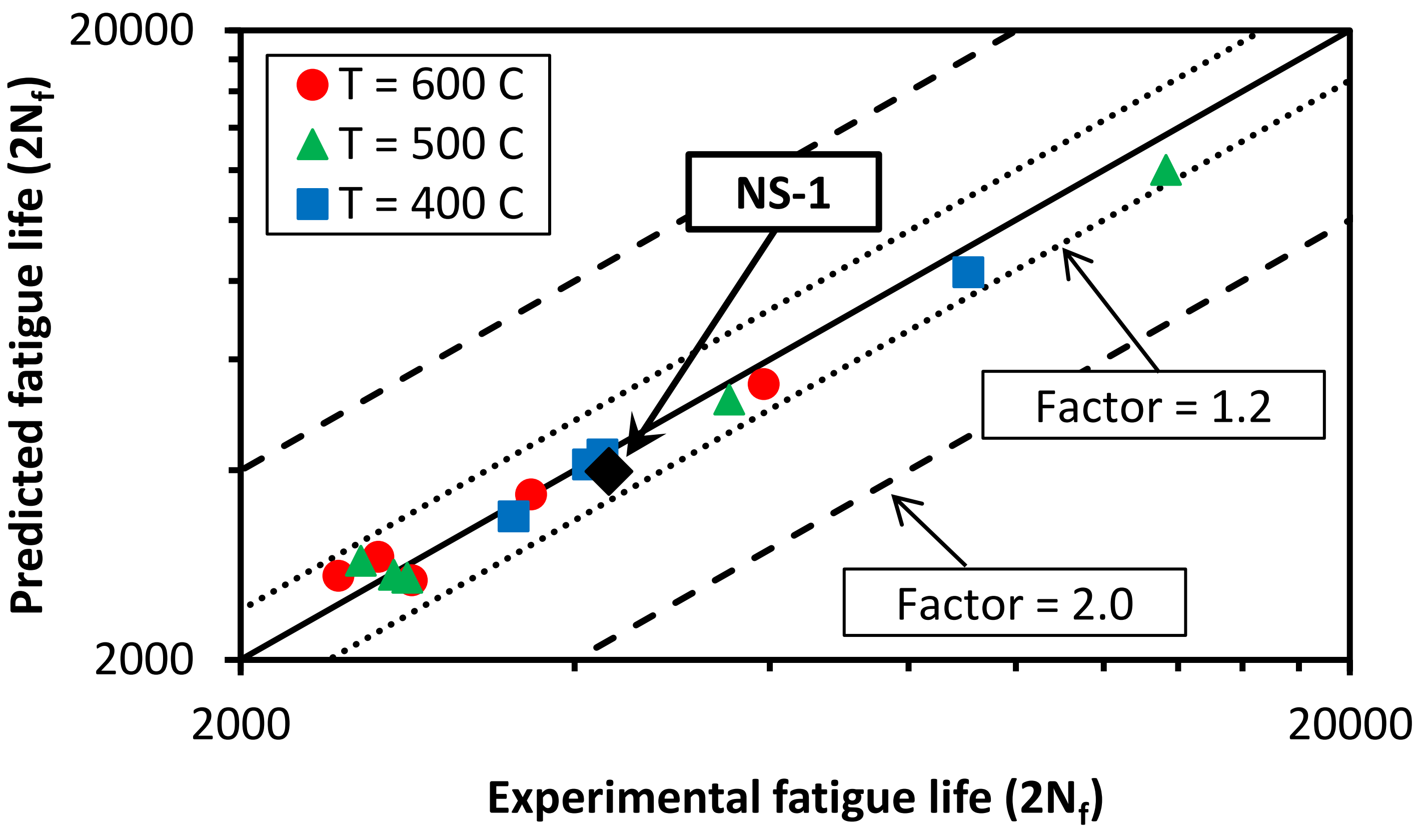
TMF-OP



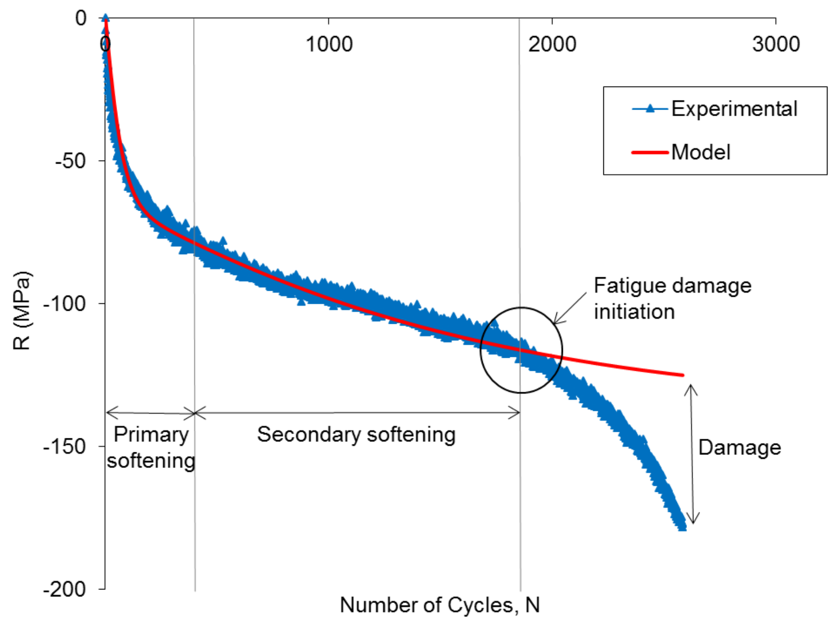



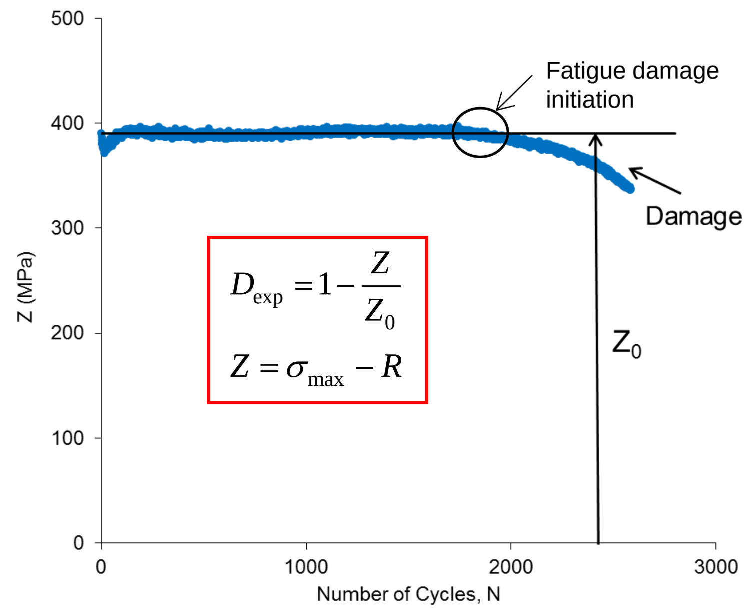
# Coffin-Manson failure prediction: P91 HTLCF




Coffin-Manson: $$\frac{\Delta\varepsilon_{in}}{2} = \varepsilon_f' \left(2N_f\right)^c$$

# Damage mechanics for HTLCF



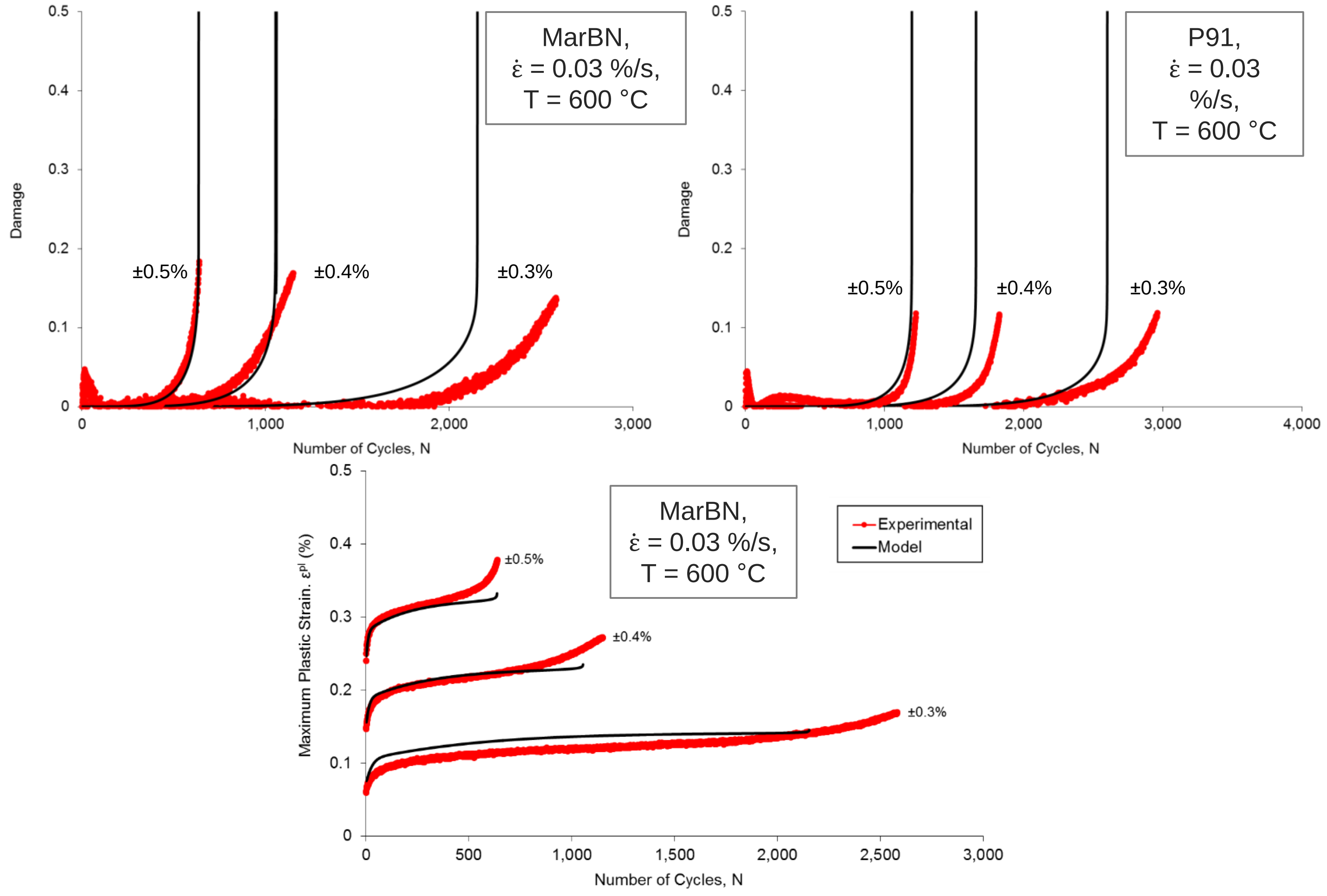




Damage: $D = 1 - \left[1 - \left(\frac{N}{N_{\mathrm{f}}}\right)^{\frac{1}{1-\phi_1}}\right]^{\frac{1}{\phi_2 - 1}}$

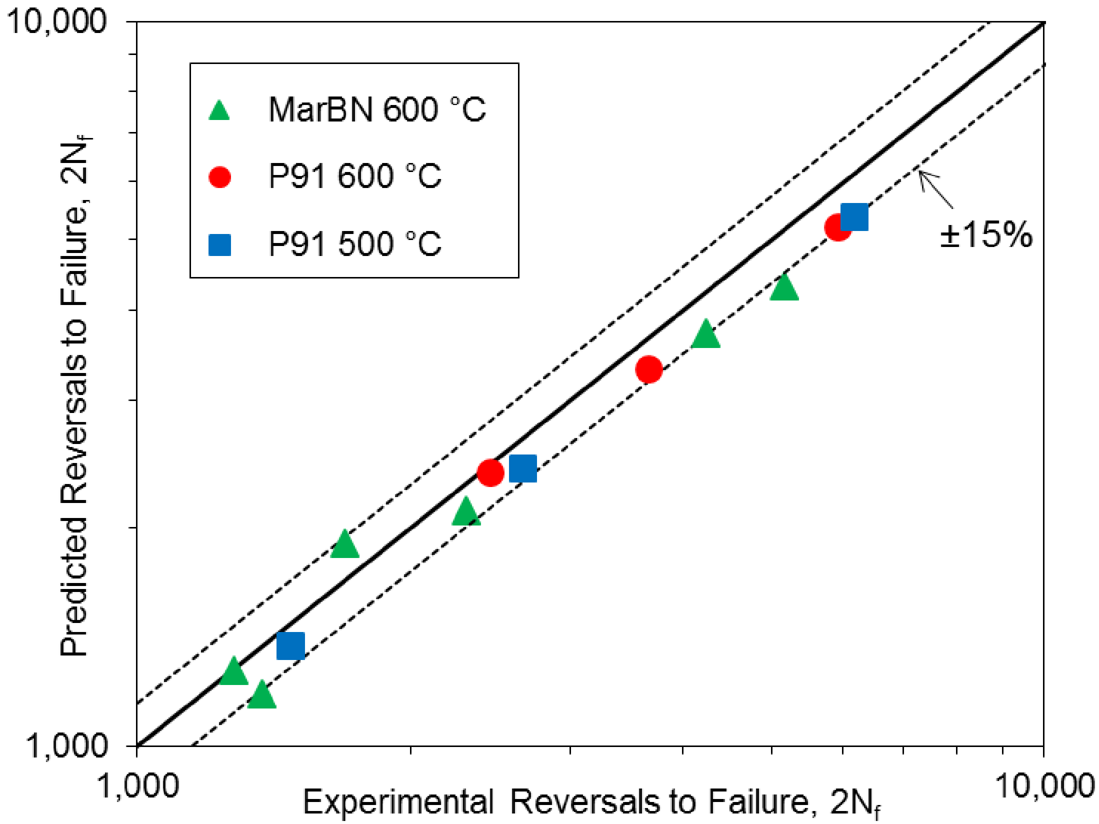
Life Prediction: $\frac{\Delta\varepsilon^{\mathrm{pl}}}{2} = \varepsilon_{\mathrm{f}}^{'}\left(2N_{\mathrm{f}}\right)^{\mathrm{c}}$

$$\frac{dD}{dN} = \left[\left(\frac{1}{1-\phi_2}\right)\left(1 - \left(\frac{N}{N_{\mathrm{f}}(N)}\right)^{\frac{1}{1-\phi_1}}\right)^{\frac{2-\phi_2}{\phi_2 - 1}}\right]\left[\left(\frac{1}{\phi_1 - 1}\right)\left(\frac{N}{N_{\mathrm{f}}(N)}\right)^{\frac{\phi_1}{1-\phi_1}}\left[N_{\mathrm{f}}(N) - N\left(\frac{1}{2c\left(2\varepsilon_{\mathrm{f}}^{'}\right)^{\frac{1}{c}}}\Delta\varepsilon^{\mathrm{pl}^{\frac{1-c}{c}}}\frac{\mathrm{d}\Delta\varepsilon^{\mathrm{pl}}}{\mathrm{dN}}\right)\right]\right]\left[N_f(N)\right]^{-2}$$

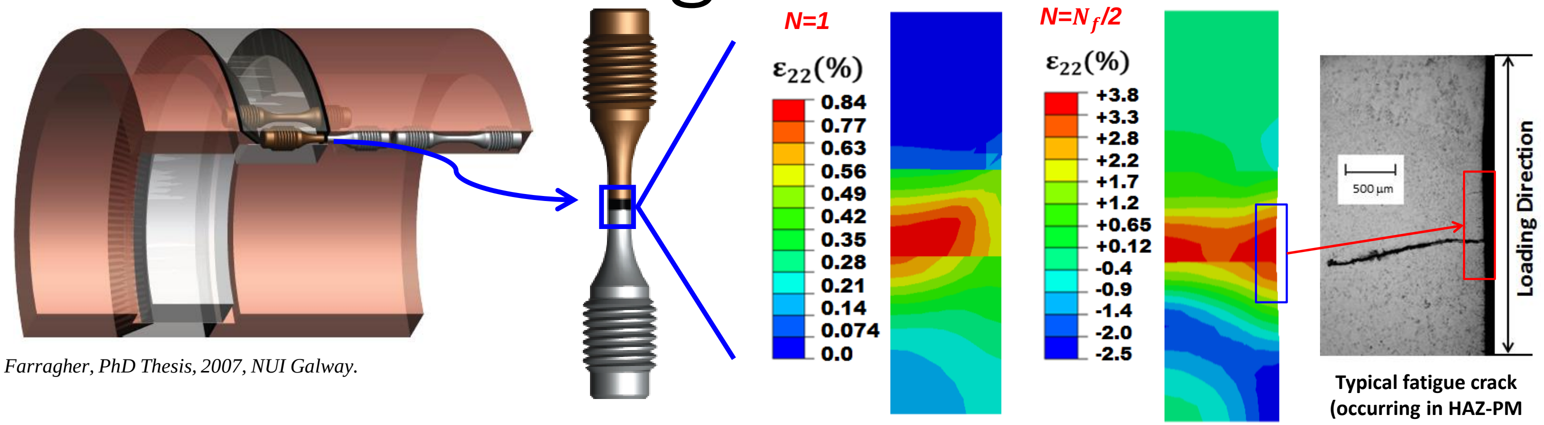
# Damage mechanics for HTLCF: P91 & MarBN



# Damage mechanics failure prediction: P91 & MarBN

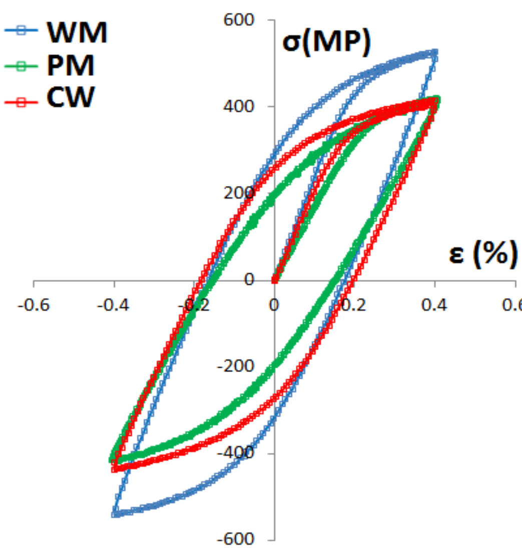


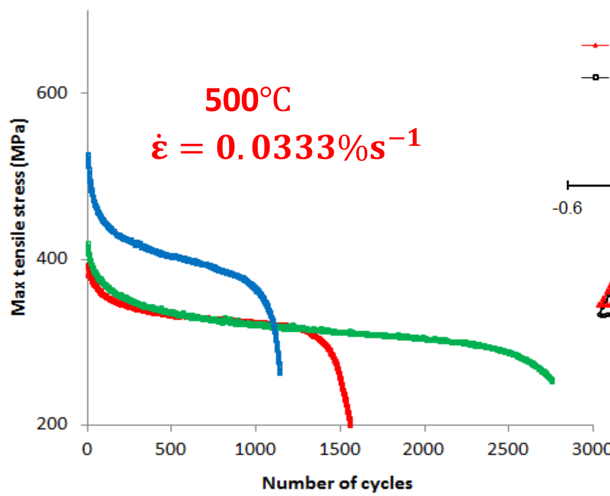
# HTLCF testing of P91 weld repair

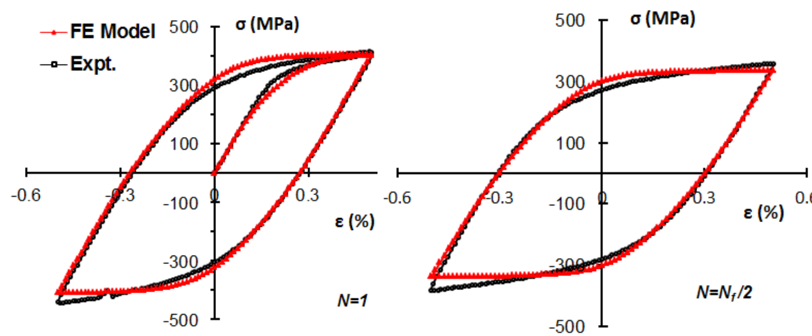



T.P. Farragher, PhD Thesis, 2007, NUI Galway.

**Typical fatigue crack (occurring in HAZ-PM interface) at type IV location**



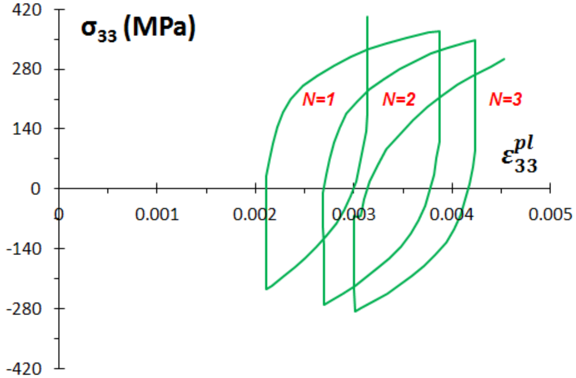



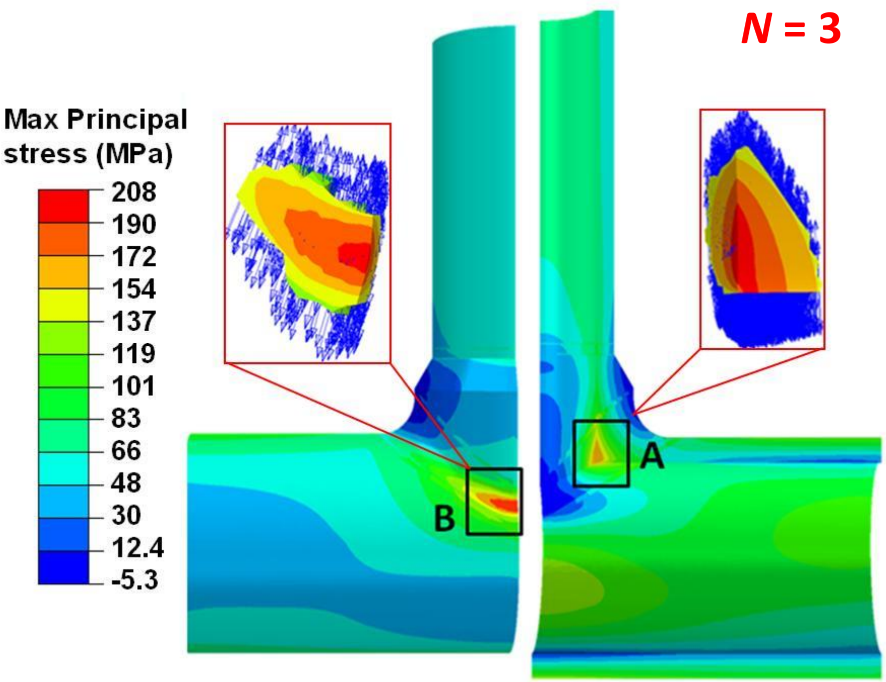
# Application to premature failure of T-piece

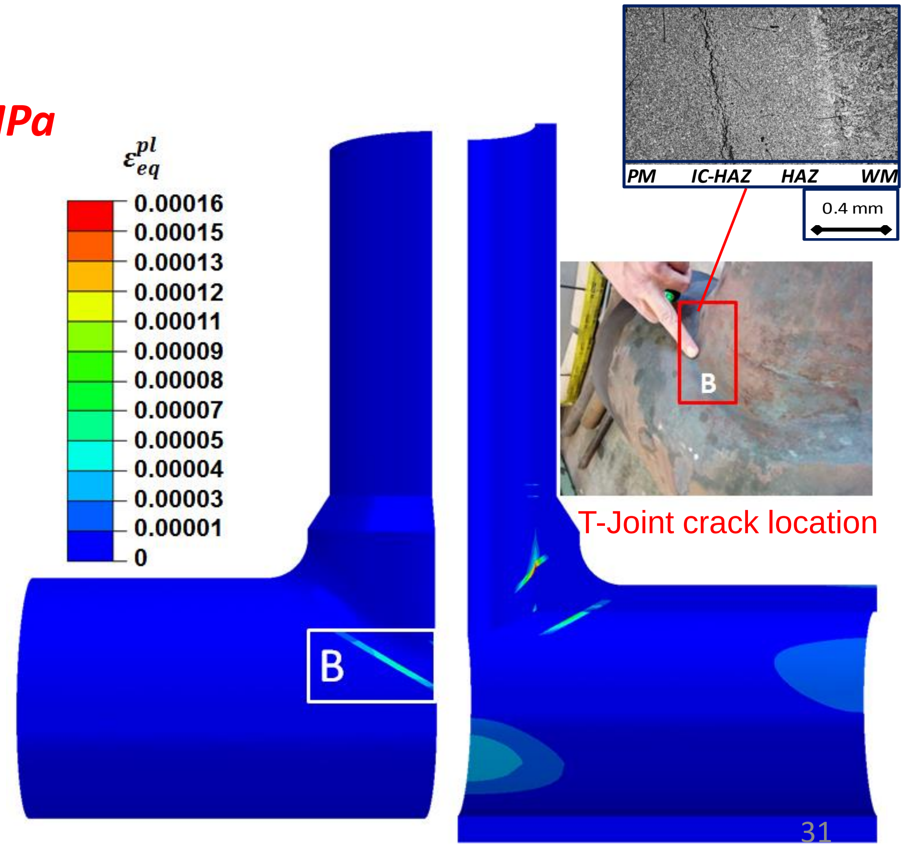
**TMF, in-phase (IP)**

**cyclic pressure and temperature (480 - 520 °C)**

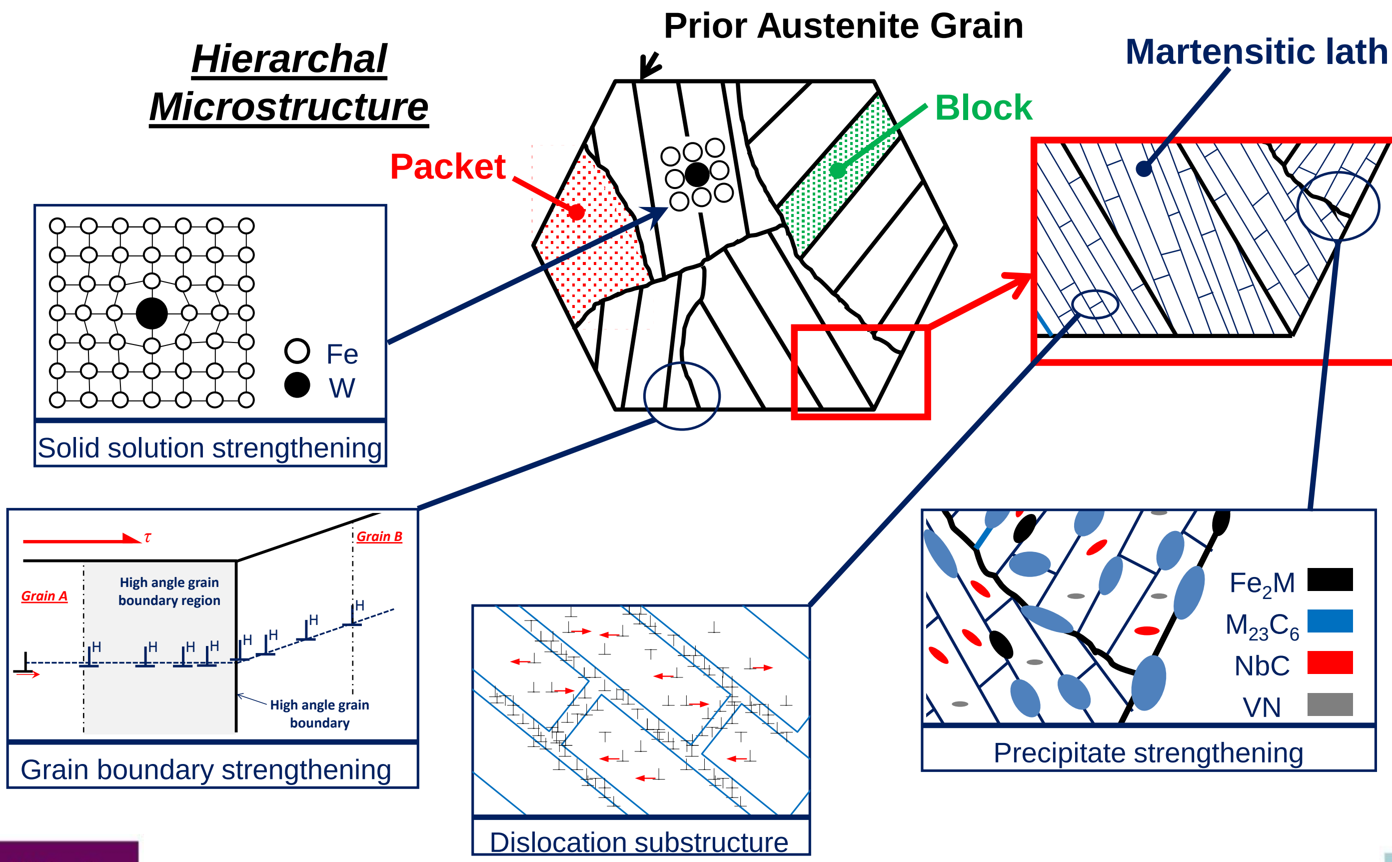



*Pi = 17 MPa*
*N = 3*



# Hierarchical micro*structure*: martensitic 9Cr steels



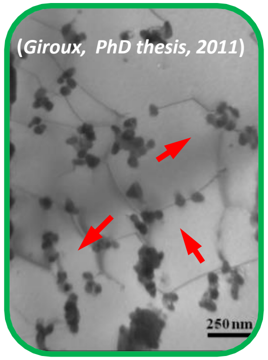
# Dislocation mechanics model

Corrosion & Oxidation

Creep

Fatigue

Damage & Life Prediction




Precipitate strengthening

$$\dot{\sigma}_{p,j} = M\mu\left[1.24\left(\frac{M\varphi bK}{n\lambda_j}\right)^{1/2}\frac{f_{eq,j}^{3/4}}{\sqrt{p_{cyc}}} + 3.09M\frac{K}{n}f_{eq,j}^{3/2}\right]\dot{\varepsilon}_{in}$$

Dislocation Pile-up

$$\dot{\sigma}_g = M^2\frac{\mu l}{\alpha d}\left(1-\frac{n_g}{n_g^{max}\,\mathrm{sgn}(\dot{\varepsilon}_{in})}\right)\dot{\varepsilon}_{in}$$

LAB hardening

$$\dot{\sigma}_w = \frac{M\mu}{1-\nu}\left(\frac{0.45bw}{2\pi\theta}\right)^{1/2}\frac{(w\dot{\theta}-\theta\dot{w})}{w^2}$$

$$\rho = \vec{\rho} + f_i\rho_i + f_w\rho_w + f_g\rho_g$$

**Evolution of dislocation density**

Kinematic back-stress

$$\sigma_b = \sigma_p + \sigma_g + \sigma_w$$

Cyclic softening

$$\sigma_y = M\left(\tau_0 + \alpha_1\mu b\sqrt{\rho}\right)$$

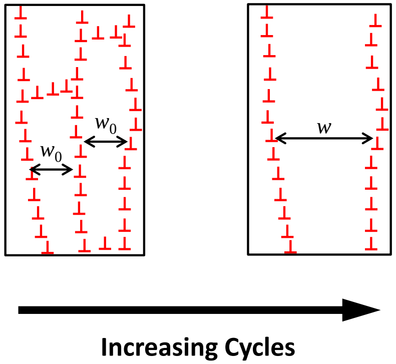
**Constitutive behaviour**

*Barrett et al., IJF 2017*

$$\dot{\varepsilon}_{in} = A\exp\left(\frac{-\Delta F}{k_B T}\right)\sinh\left[\frac{\Delta V}{Mk_B T}\left(|\sigma-\sigma_b|-\sigma_y\right)\right]$$

Lath widening

$$w = \frac{w_0\rho_{w,0}}{\rho_w}$$



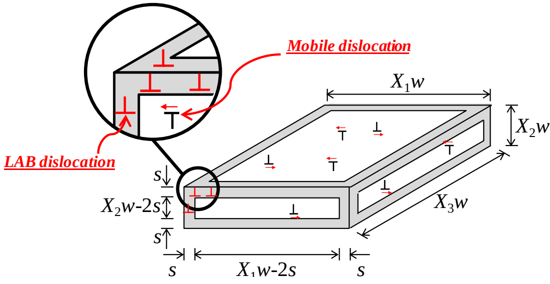

**LAB dislocation density:**

$$\rho_w = \frac{1}{2s}\frac{w(X_1+X_2+X_3)}{s_0\left(w(X_1+X_2+X_3)-\frac{s_0}{2}\right)}$$

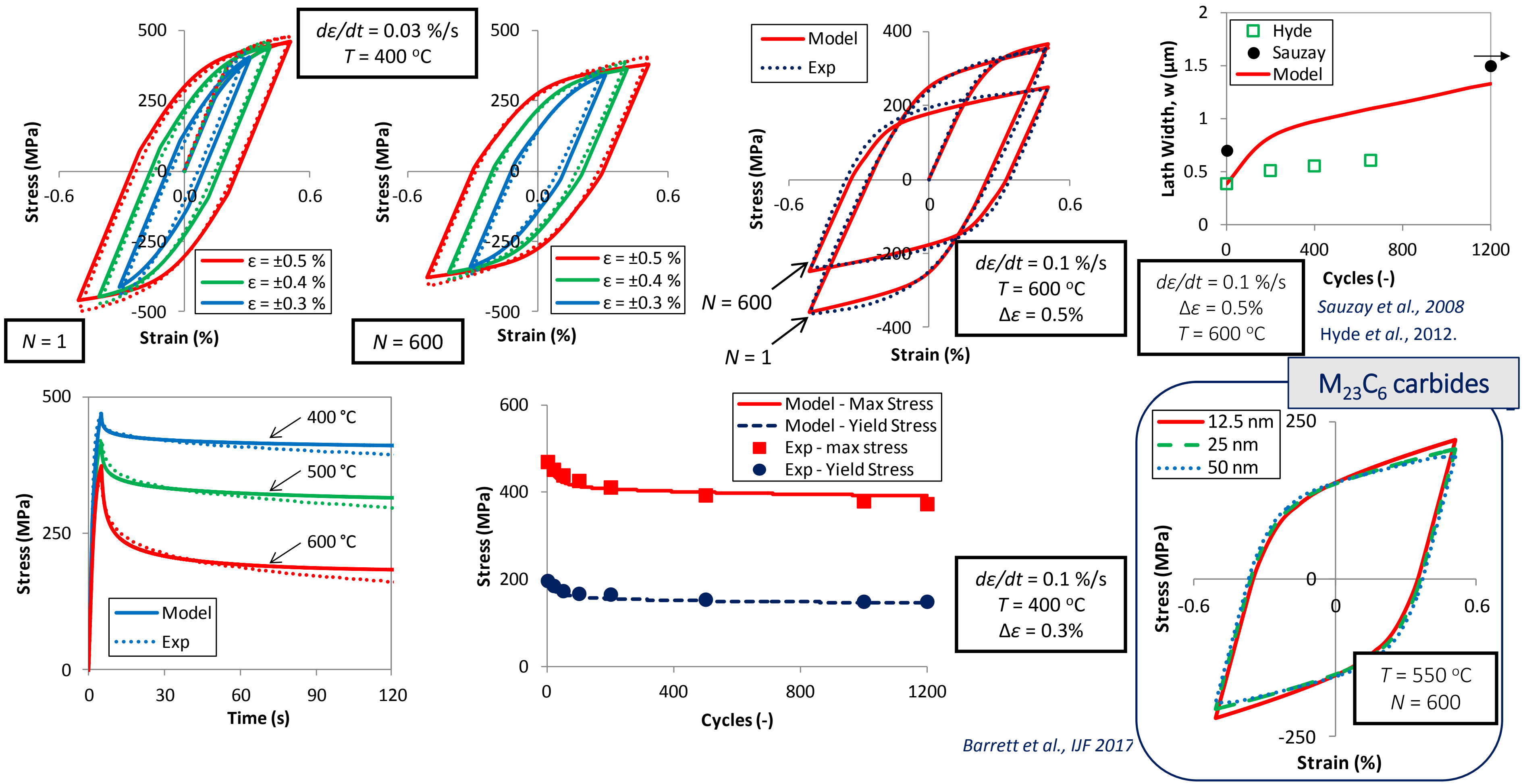
**Angle of lath misorientation :**

$$\dot{\theta} = \frac{2b^2}{\theta_0}\dot{\rho}_w - \frac{b^3}{\theta_0^2(X_1+X_2+X_3)}\left(\frac{w\dot{\rho}_w-\rho_w\dot{w}}{w^2}\right)$$

**Lath geometry model**



# Dislocation mechanics model: P91



# Conclusions

- HTLCF and TMF experimental and viscoplastic constitutive modelling characterization for ex-service P91 and cast MarBN martensitic steels:
  - Part of broad Materials Design Tool (MDT) under development with SFI MECHANNICS project
  - Physically-based modelling needed: e.g. cyclic softening (sub-grain coarsening, decrease in dislocation density)
  - Multi-scale, multi-physics modelling needed: Inclusions and oxidation are key phenomena for fatigue crack initiation and damage
  - Applications to notch specimens and real plant components under realistic thermal loading
- Current work: through-process, physically-based models for welding, heat treatment and thermo-mechanical fatigue

# Acknowledgements

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