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

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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
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CO₂ emissions

David J.C. MacKay. Sustainable Energy – without the hot air.
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The rise of wind energy

Gross Final Electricity Consumption

- ×5 increase
- +1.8%/year
  2007 - 2015

Total wind capacity

- ×20 increase
- +182 MWe/year
  2003 - 2015

WindEurope.org

Clean, efficient, sustainable energy

2 % Efficiency Gain $\leftrightarrow$ 5 % CO$_2$ Reduction

Current subcritical (SC) plant

Ultra-supercritical (USC) plant

Adapted from: Abson and Rothwell, Int. Materials Reviews, 58 (2013) 437-473
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.
Next generation power plant materials

Creep, T = 650 °C

Thermal fatigue parameter

\[ R_{TF} = \frac{k\sigma_y}{\alpha_{COE} E} \]

MarBN composition: Abe et al., 2008
Need for higher temperature materials

Higher temperature operation (~650 °C).
Enhanced creep performance compared with P92 steel

Fatigue behaviour of MarBN…

Suppression of Type IV failure

A through-process materials design tool for welds

- Chemical composition
- Heat treatment simulations
- Welding process analysis
- Physically-based macro-scale material model
- Component level modelling

Component level modelling

- Realistic plant geometries and loading
- Validation via TMF/creep test data
- SEM/TEM validation
- Multi-scale modelling approach

Meso-micro-mechanical modelling

- Martensitic transformation
- Normalize
- Tempering

Heat treatment simulations

Identification of initial conditions

SEM/TEM validation

Validation via TMF/creep test data

Physically-based macro-scale material model

Oxidation-corrosion fatigue-creep damage model

Plant life assessment

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

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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

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Strain-range (%)</th>
<th>Strain-rate (%/s)</th>
<th>Waveform</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTLCF 650 °C</td>
<td>±0.5</td>
<td>0.1, 0.01</td>
<td>$R_{\varepsilon} = -1$ (Triangular)</td>
</tr>
<tr>
<td>HTLCF 600 °C</td>
<td>±0.5</td>
<td>0.1, 0.0333, 0.01</td>
<td>$R_{\varepsilon} = -1$ (Triangular)</td>
</tr>
<tr>
<td></td>
<td>±0.4</td>
<td>0.033, 0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>±0.3</td>
<td>0.033, 0.01</td>
<td></td>
</tr>
<tr>
<td>Cyclic Dwell</td>
<td>±0.5</td>
<td>0.1</td>
<td>1 hour hold period</td>
</tr>
<tr>
<td>600 °C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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**TMF Testing**

**Load Cell**  
**Upper Grip**  
**Frame**  
**Lower Grip**  
**Actuator**  

**Induction Coil**  
**High Temperature Extensometer**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Strain Rate (%/s)</th>
<th>Strain Range (±%)</th>
<th>Wave time (s)</th>
<th>Heating/ Cooling rate (°C/s)</th>
<th>Waveform</th>
<th>Phase</th>
<th>Test Type</th>
<th>Specimen Type</th>
<th>Comment</th>
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<td>400-600</td>
<td>0.01</td>
<td>0.5</td>
<td>320</td>
<td>2</td>
<td>R&lt;sub&gt;e&lt;/sub&gt;= -1 Triangular</td>
<td>In-phase</td>
<td>Anisothermal</td>
<td>Hollow</td>
<td>2 min Hold</td>
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<td>Hollow</td>
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</tr>
<tr>
<td></td>
<td>0.0333333</td>
<td>0.5</td>
<td>180.00006</td>
<td>6.6666666</td>
<td>R&lt;sub&gt;e&lt;/sub&gt;= -1 Triangular</td>
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<td>0.025</td>
<td>0.5</td>
<td>200</td>
<td>5</td>
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**TMF in phase (TMF-IP):**

**TMF out of phase (TMF-OP):**

- **Mechanical Strain**
- **Temperature**
HTLCF Test Results: MarBN

\[ T = 600 \, ^\circ C \]

**Strain-rate effect**

- SR=0.1 %/s
- SR=0.01 %/s
- SR=0.001 %/s

**Max Tensile Stress (MPa)**

- \( \varepsilon = \pm 0.5 \% \)
- \( \varepsilon = \pm 0.4 \% \)
- \( \varepsilon = \pm 0.3 \% \)

- \( \frac{d\varepsilon}{dt} = 0.033 \%/s \)

**Cyclic softening**

- \( \varepsilon = 0.5 \% \)
- \( \frac{d\varepsilon}{dt} = 0.01 \%/s \)

**Strain-range response**

- \( \varepsilon = \pm 0.5 \% \)
- \( \varepsilon = \pm 0.4 \% \)
- \( \varepsilon = \pm 0.3 \% \)

\( N = \text{Half life} \)

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HTLCF and TMF results: ex-service P91

Fatigue life

Plastic strain range, $\Delta \varepsilon_{pl}/2$

Number of reversals to failure, $2N_f$

Strain-rate effect

$\varepsilon = \pm 0.5 \%$

$\frac{d\varepsilon}{dt}=0.025 \%/s$

$\varepsilon = \pm 0.4 \%$

$\frac{d\varepsilon}{dt}=0.033 \%/s$

Representative TMF

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Enhanced cyclic performance of MarBN

Increasing lath width

Total strain range, $\Delta \varepsilon /2$

Number of reversals to failure, $2N_f$

AR-P91
ES-P91
MarBN

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

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Process-induced defects: MarBN fatigue

High volume fraction of casting defects and inclusions

3D X-ray CT scan

Micro-crack initiation at inclusions

Secondary cracking

Fatigue striations

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

**\( \dot{\varepsilon}_{CR} = \alpha_{CR} \sinh(\beta_{CR} \sigma) \)**
Unified cyclic viscoplasticity model

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

‘Yield’ function: \( f = J(s - x) - R - k \)

Cyclic softening:
\[
R = R_1 + R_2 \quad \dot{R}_i = b_i (Q_i - R_i) \dot{p} + \left( \frac{1}{b_i} \frac{\partial b_i}{\partial T} + \frac{1}{Q_i} \frac{\partial Q_i}{\partial T} \right) R_i \dot{T}
\]

Kinematic back-stress:
\[
\chi = \chi_1 + \chi_2 \quad \dot{\chi}_i = \frac{2}{3} C_i \dot{\varepsilon}^{in} - \gamma_i \chi \dot{p} + \frac{1}{C_i} \frac{\partial C_i}{\partial T} \chi \dot{T}
\]
Parameter identification

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


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Calibration and validation: P91

\[ \varepsilon = \pm 0.5 \% \]
\[ \frac{d\varepsilon}{dt} = 0.1 \%/s \]

400 °C

500 °C

600 °C

Stress (MPa) vs. Mechanical Strain (%) for different temperatures and strains. The graphs show experimental (Exp) and model (Model) data. The strains considered are ±0.5 %, ±0.4 %, and ±0.3 %. The stress-strain curves are depicted for each temperature level, with the number of data points (N) specified for each case.
Softening effect: P91

\[ \varepsilon = \pm 0.5 \% \]
\[ \frac{d\varepsilon}{dt} = 0.25 \%/s \]

\[ \varepsilon = \pm 0.4 \% \]
\[ \frac{d\varepsilon}{dt} = 0.033 \%/s \]
Strain-rate effect: P91

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TMF modelling: P91

\( \frac{d\varepsilon}{dt} = 0.033 \%/s \)

- **TMF-IP**
- **TMF-OP**

**Mechanical Strain**

**Temperature**

**Time (s)**

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Coffin-Manson failure prediction: P91 HTLCF

\[ \frac{\Delta \varepsilon_{\text{in}}}{2} = \varepsilon'_f \left(2N_f\right) \]

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**Damage mechanics for HTLDCF**

\[ D = 1 - \left( \frac{N}{N_f} \right)^{\frac{1-\phi_2}{\phi_1}} \]

\[ \frac{dD}{dN} = \left[ \left( \frac{1}{1-\phi_2} \right) \left( 1 - \left( \frac{N}{N_f(N)} \right)^{\frac{1-\phi_1}{\phi_1}} \right) \right] \left[ \left( 1 - \frac{N}{N_f(N)} \right) ^{\phi_1} \right] \left[ N_f(N) - N \left( \frac{1}{2c(2\varepsilon_f)} \Delta \varepsilon^{pl \frac{1-c}{c}} \frac{d\Delta \varepsilon^{pl}}{dN} \right) \right] \left[ N_f(N) \right]^{-2} \]

Fatigue damage initiation

Fatigue damage

Life Prediction:

\[ \frac{\Delta \varepsilon^{pl}}{2} = \varepsilon_f \left( 2N_f \right)^c \]

\[ Z = \sigma_{\text{max}} - R \]

\[ D_{\text{exp}} = 1 - \frac{Z}{Z_0} \]

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Damage mechanics for HTLCF: P91 & MarBN

MarBN, \( \dot{\varepsilon} = 0.03 \% / s, \) 
\( T = 600 \, ^\circ C \)

MarBN, \( \dot{\varepsilon} = 0.03 \% / s, \) 
\( T = 600 \, ^\circ C \)

P91, \( \dot{\varepsilon} = 0.03 \% / s, \) 
\( T = 600 \, ^\circ C \)

MarBN, \( \dot{\varepsilon} = 0.03 \% / s, \) 
\( T = 600 \, ^\circ C \)
Damage mechanics failure prediction: P91 & MarBN
HTLDCF testing of P91 weld repair

500°C
\[ \dot{\varepsilon} = 0.0333 \text{%s}^{-1} \]

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Application to premature failure of T-piece

PM IC-HAZ HAZ WM
Saddle Point
0.4 mm

$P_i = 17 \text{ MPa}$
$N = 3$

TMF, in-phase (IP)
cyclic pressure and temperature (480 - 520 °C)

Max Principal stress (MPa)

208   190   172   154   137   119   101   83   66   48   30   12.4   -5.3

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Hierarchical microstructure: martensitic 9Cr steels

**Hierarchal Microstructure**

- **Solid solution strengthening**
- **Grain boundary strengthening**
- **Dislocation substructure**
- **Precipitate strengthening**

**Prior Austenite Grain**

- **Martensitic lath**
- **Packet**
- **Block**

**Chemical Phases**

- Fe
- W
- Fe$_2$M
- M$_{23}$C$_6$
- NbC
- VN

**Workshop Details**

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Dislocation mechanics model

Corrosion & Oxidation → Creep → Fatigue → Damage & Life Prediction → Evolution of dislocation density

\[ \rho = \rho_0 + f_1 \rho_1 + f_w \rho_w + f_\theta \rho_\theta \]

\[ w = \frac{w_0 \rho_{w,0}}{\rho_w} \]

Lath widening

LAB dislocation density:

Angle of lath misorientation:

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

\[ \dot{\theta} = \frac{2b_2^2}{\theta_0} \dot{\rho}_w - \frac{b_1^3}{\theta_0^2} \frac{w \dot{\rho}_w - \rho_w \dot{w}}{w^2} \]

Precipitate strengthening

Dislocation Pile-up

LAB hardening

Constitutive behaviour

\[ \dot{\varepsilon}_{\text{in}} = A \exp \left( -\frac{\Delta F}{k_B T} \right) \sinh \left( \frac{\Delta V}{M k_B T} \left( |\sigma - \sigma_y| - |\sigma_0| + \sigma_y \right) \right) \]

Barrett et al., IJF 2017

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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 MECHANICS 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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