Cross-Cutting Issues Relating to High Temperature Integrity

Stuart Holdsworth

High Temperature Integrity
Mechanical Integrity for Energy Systems

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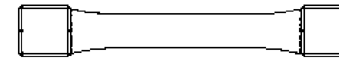
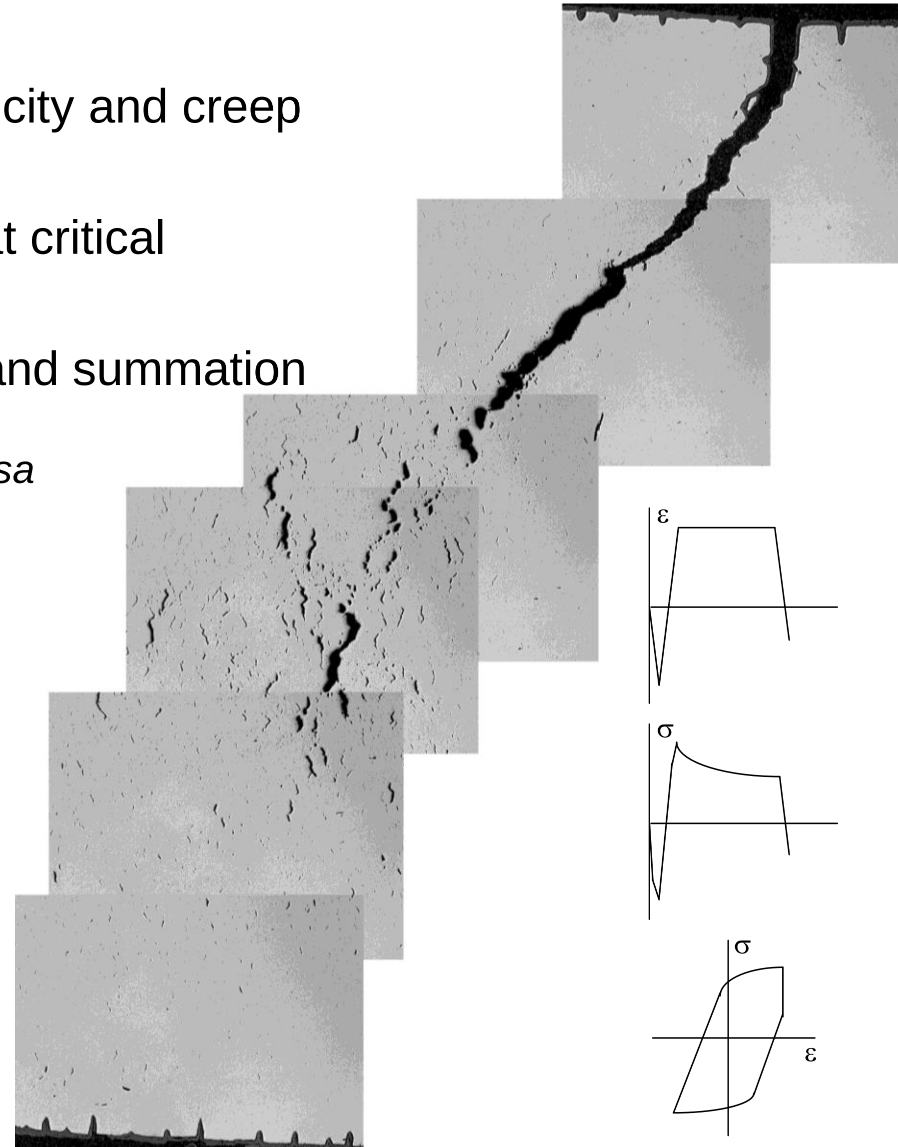
Materials Science & Technology

Cross-cutting issues relating to high temperature integrity

Structure of presentation



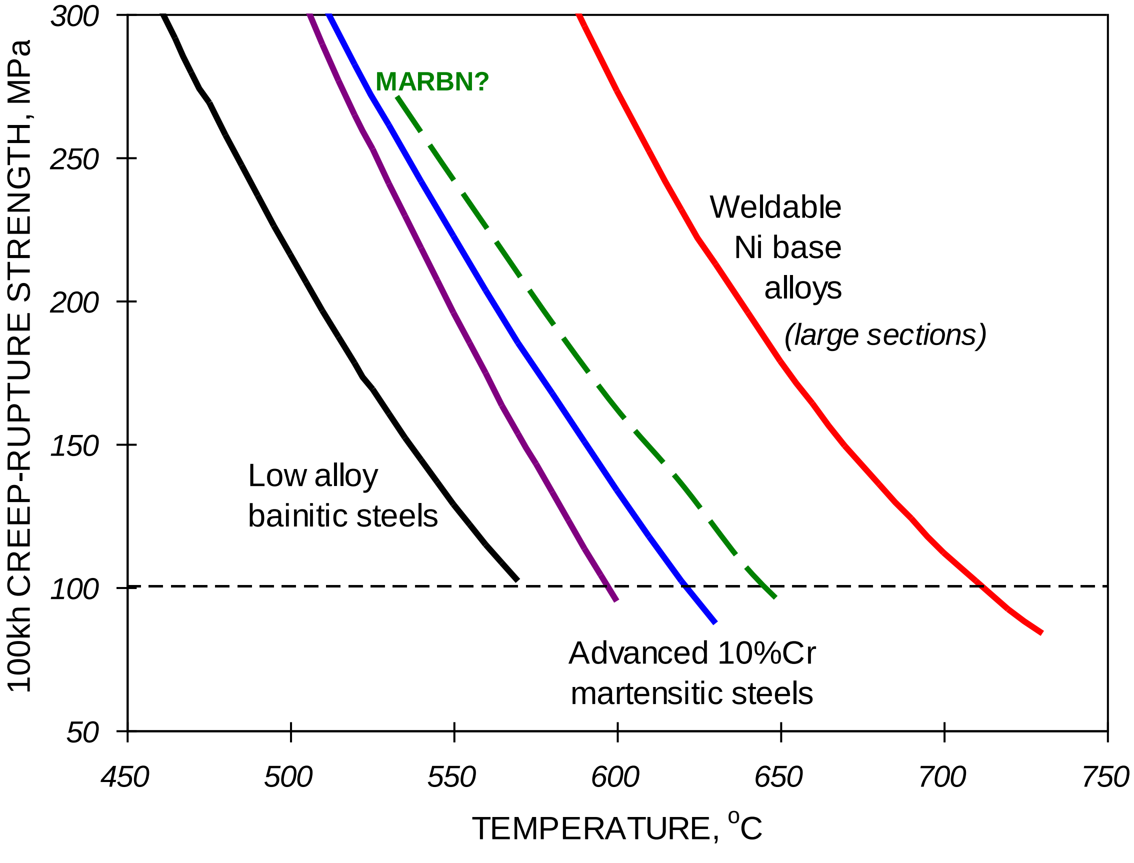
- Background and Introduction
- Constitutive modelling of cyclic-plasticity and creep deformation properties
- Determination of stress/strain state at critical locations
- Creep fatigue damage assessment and summation
  - *LICON*
  - *Effects of fatigue on creep and vice-versa*
- Concluding remarks

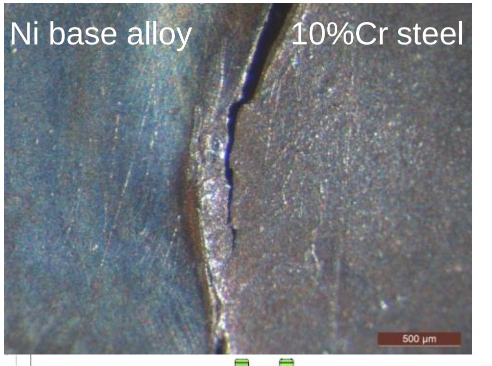


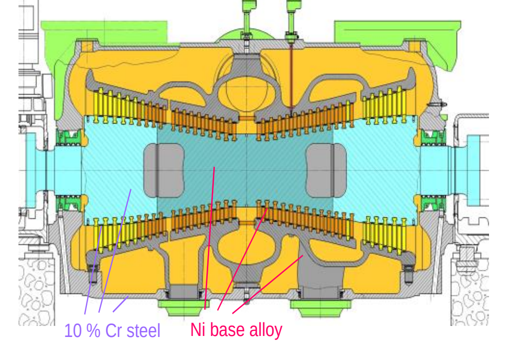
- *Importance of familiarity with material characteristics / deformation response (e.g. creep-fatigue deformation and damage interactions)*

Cross cutting issues relating to high temperature integrity

Fossil turbomachinery material solutions with wider application

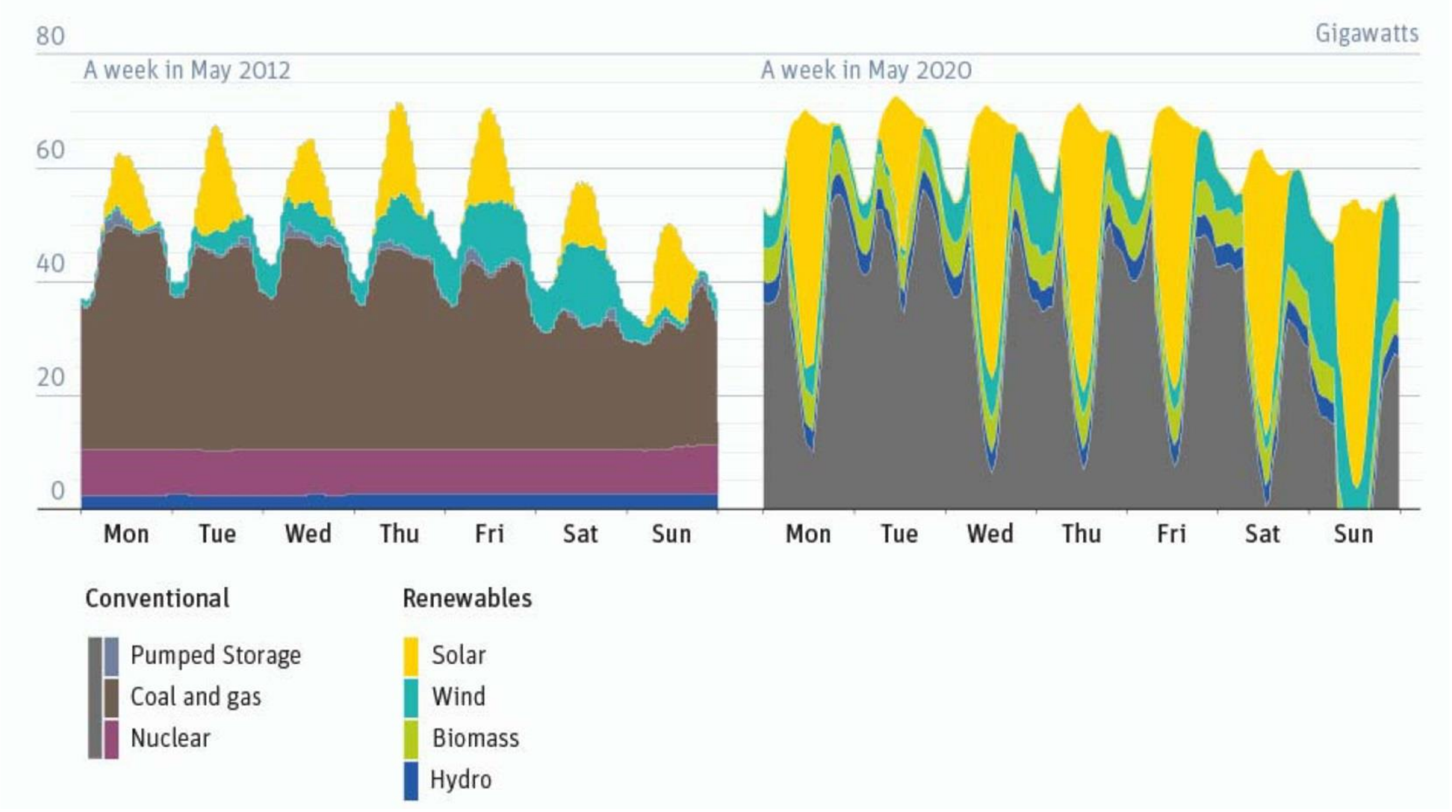






Renewables need flexible back up not baseload

Estimated power demand over a week in 2012 and 2020 (Germany)



Creep-fatigue damage assessment: Generic flow diagram

Defect-free components

- **Fatigue damage fraction**

  $D_F = N_{CF} / N_{LCF}$

- **Creep damage fraction**
  - *Time fraction*

    $D_{C(t)} = N_{CF} . \int_0^t dt / t_r(\sigma)$

  - *Ductility exhaustion*

    $D_{C(\varepsilon)} = N_{CF} . \int_0^t \dot{\varepsilon} . dt / \varepsilon_r(\dot{\varepsilon})$

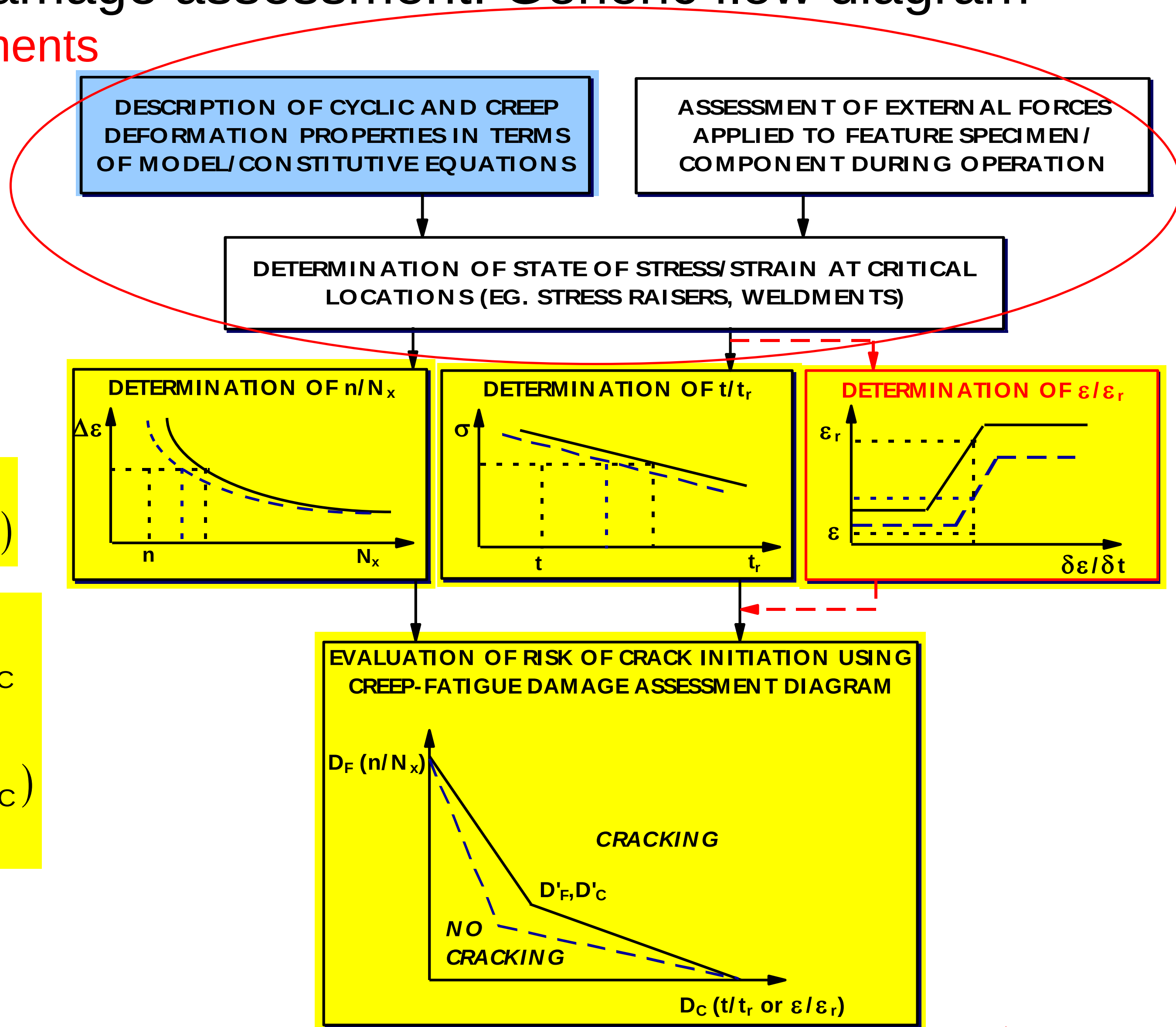
- **Damage summation**

  $D_F = 1 - D_C . (1 - D'_F) / D_C$

  for $D_C < D'_C$

  $D_F = [1 - D_C] . D'_F / (1 - D_C)$

  for $D_C > D'_C$



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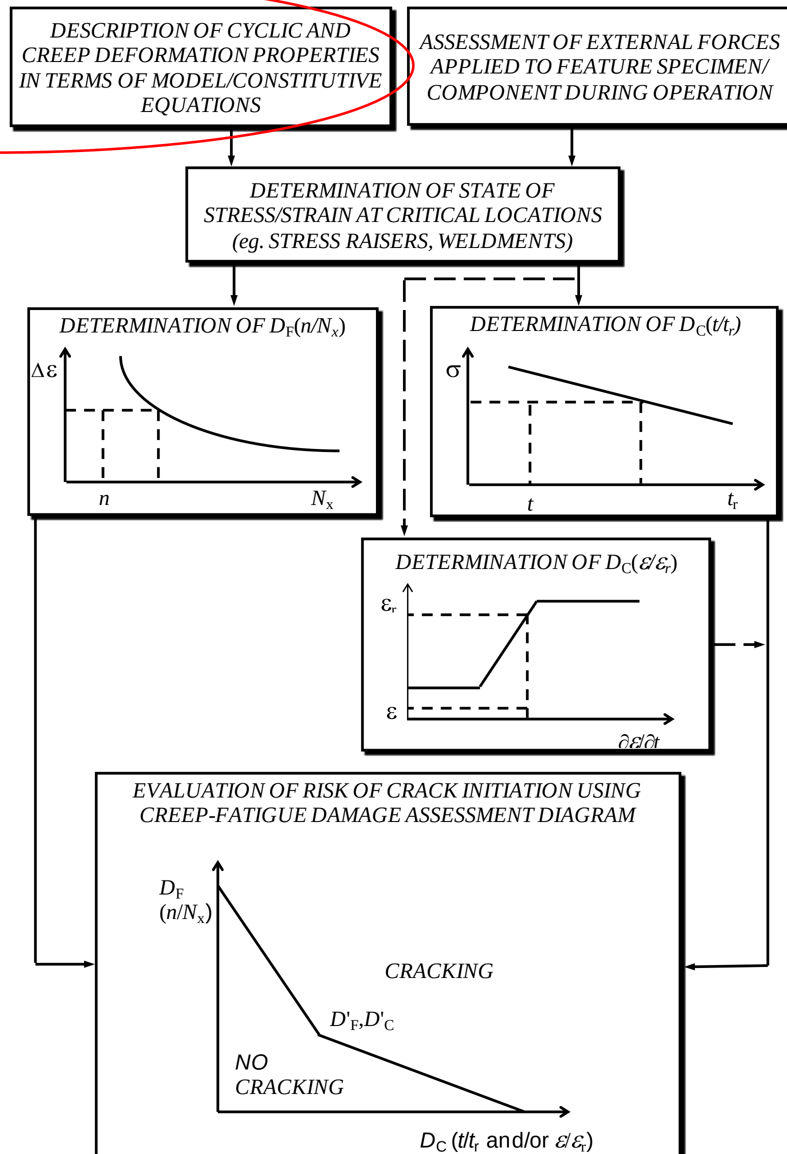
Creep-fatigue damage assessment

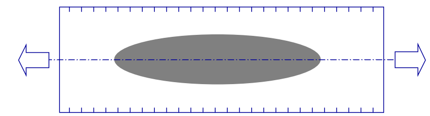
Generic flow diagram

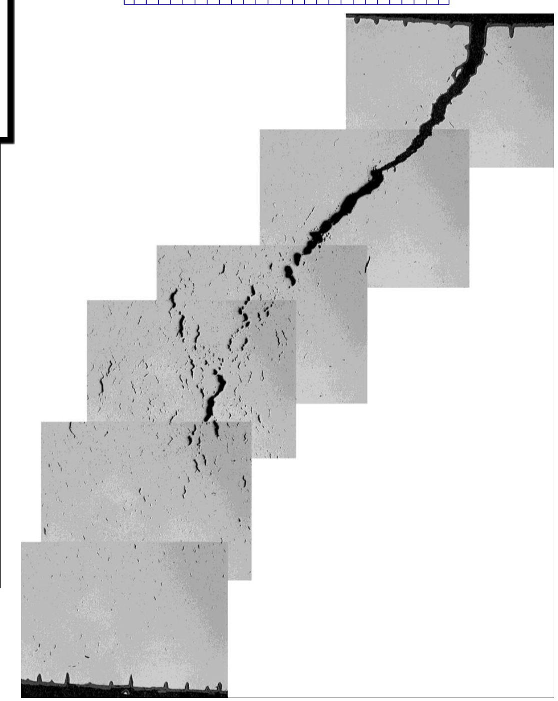
Constitutive modelling

FEA simulation

Damage assessment







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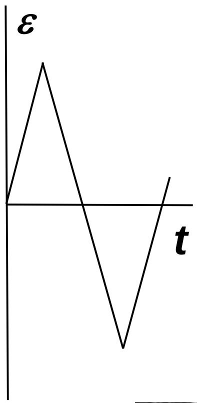
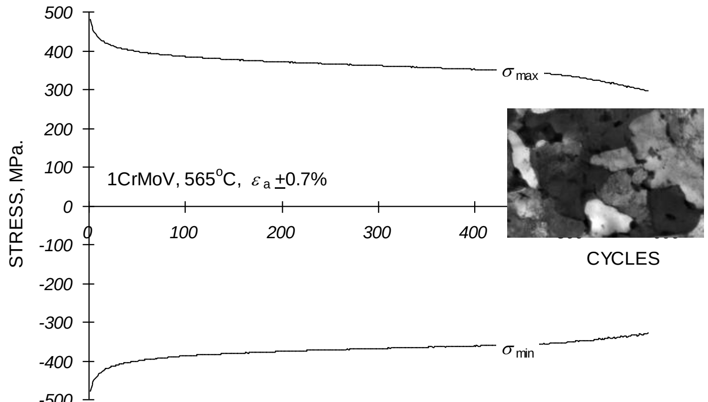
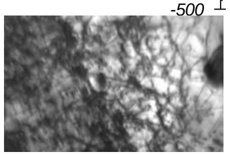
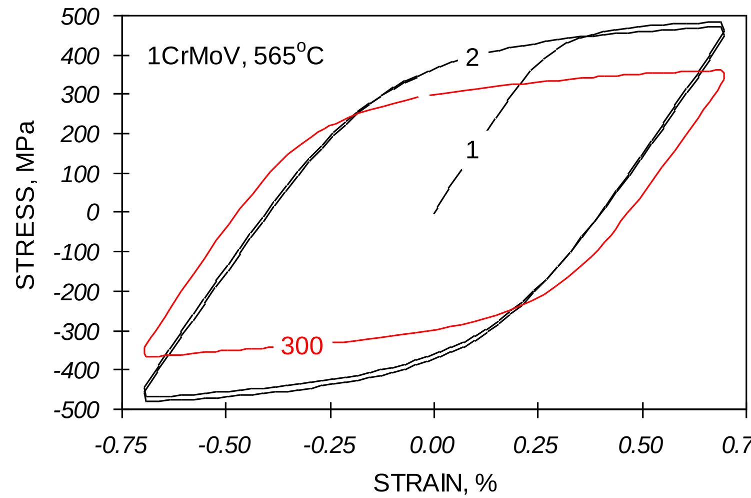
Response to strain-controlled LCF cycles

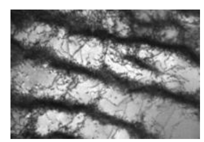
Cyclic softening (1CrMoV, 565ºC), cyclic hardening (TP316, 550ºC)

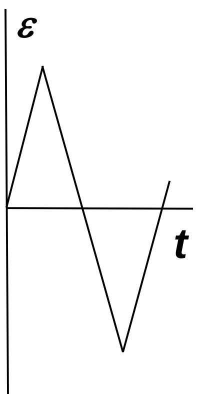


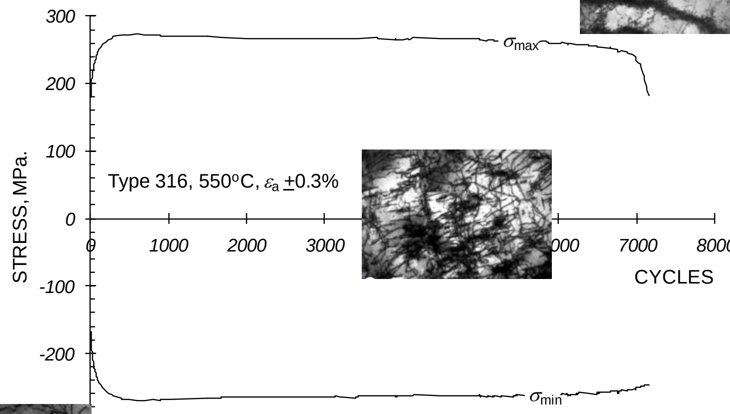


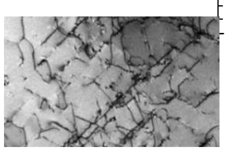


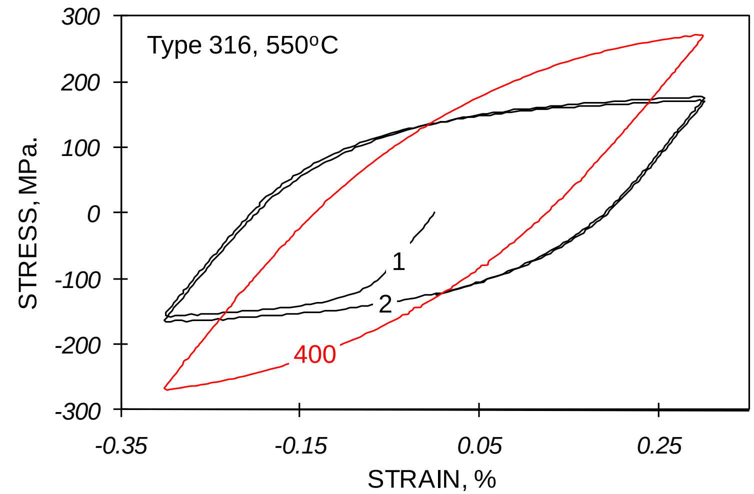












Cross-cutting issues relating to high temperature integrity

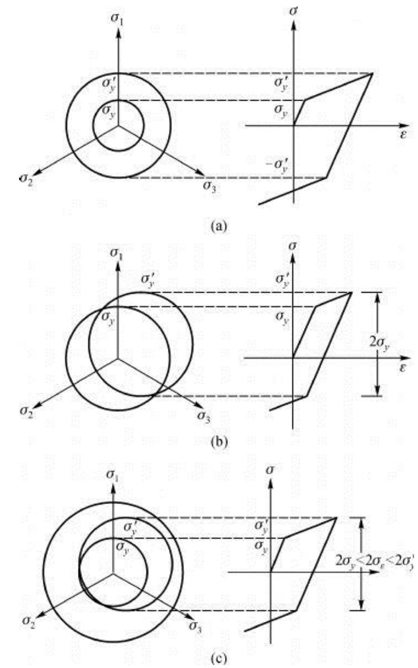
Representation of cyclic plasticity and creep deformation properties

- Cyclic plasticity (non-unified or unified)

$$\varepsilon_{\mathrm{p}} = \int_0^t \sqrt{\tfrac{2}{3}\sum_i \sum_j \dot{\varepsilon}_{\mathrm{p},ij} \cdot \dot{\varepsilon}_{\mathrm{p},ij}}\,.\partial t \qquad \sigma = \frac{C_k}{\gamma_k}\left(1 - e^{-\gamma \varepsilon_{\mathrm{p}}}\right) + \sigma_o$$

$$\dot{\boldsymbol{\alpha}}_{k,ij} = C_k \dot{\varepsilon}_{\mathrm{p}} \left(\frac{\sigma_{ij} - \alpha_{ij}}{\sigma_{\mathrm{o}}} \right) - \gamma_k \alpha_{k,ij} \dot{\varepsilon}_{\mathrm{p}} + \frac{\alpha_{k,ij}}{C_k} \dot{C}_k$$

$$f = J_2\left(\boldsymbol{\sigma} - \boldsymbol{\alpha}\right) = \sigma_{\mathrm{o}}$$

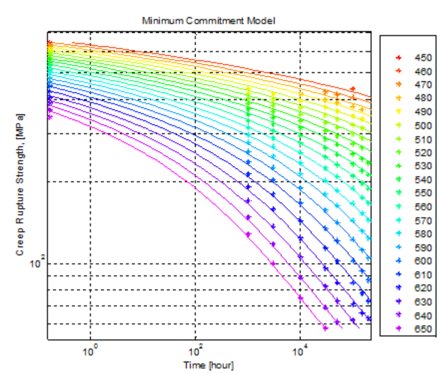


- Creep (non-unified)

$$\varepsilon_{\mathrm{C}} = A\sigma^n t^p + \dot{\varepsilon}_{\mathrm{C,min}} t$$

$$\varepsilon_{\mathrm{C}} = \frac{\varepsilon_{\mathrm{D}}\left(R_{\mathrm{R}}/R_{\mathrm{D}} - 1\right)}{\left[R_{\mathrm{R}}/\sigma - 1\right]} = \frac{\varepsilon_\chi}{\left[R_{\mathrm{R}}/\sigma - 1\right]}$$

  - *Modelled to give consistency for all* $(T,\sigma)_{application}$

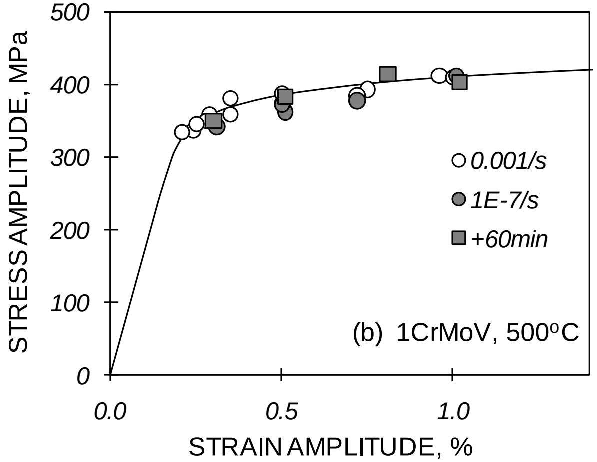


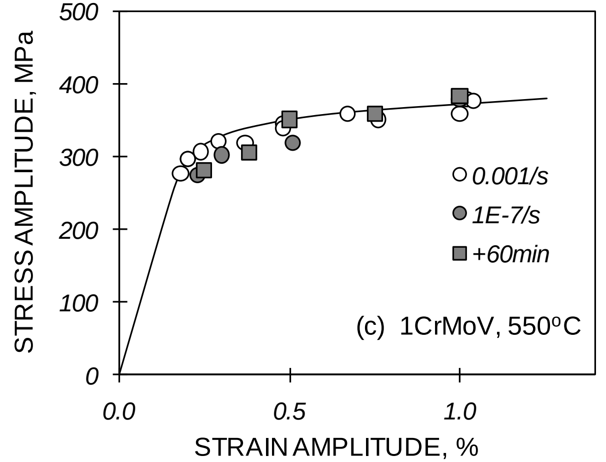
- Non-unified or unified constitutive modelling
  - *Application dependent*
  - *Data requirements*
  - *Flexibility for multi-cast modelling*

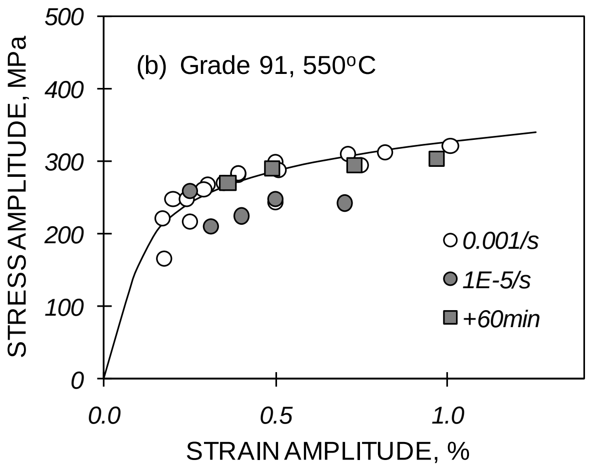
Cross-cutting issues relating to high temperature integrity

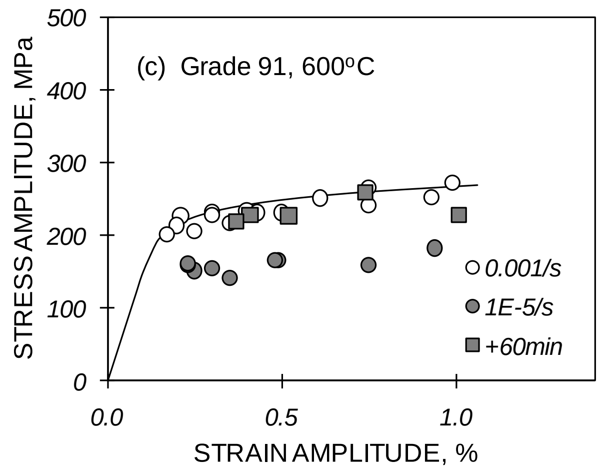
Representation of cyclic plasticity and creep deformation properties

- Non-unified or unified constitutive modelling





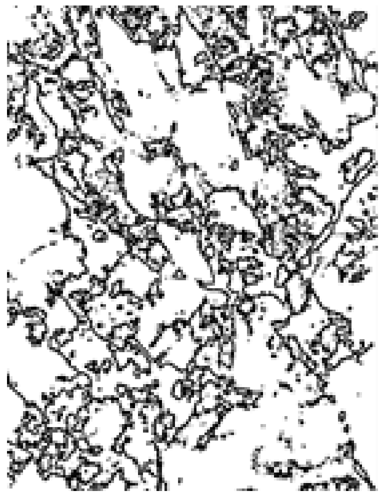




Creep-fatigue interaction in advanced martensitic steels

Influence of cyclic and creep-fatigue loading on sub-grain structure

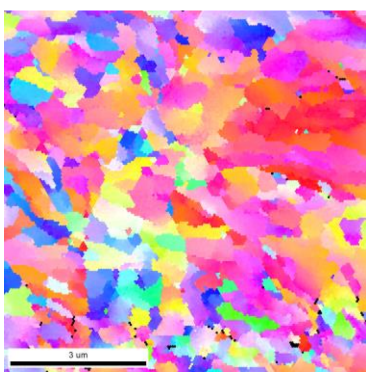
Quality heat treated

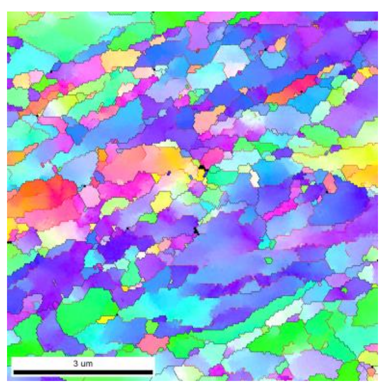


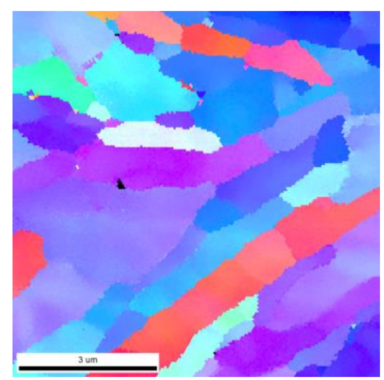
Pure fatigue loading

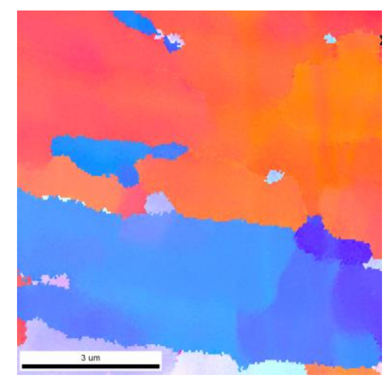
Creep-fatigue loading

9%Cr pipe [Fournier]









9%Cr turbine rotor

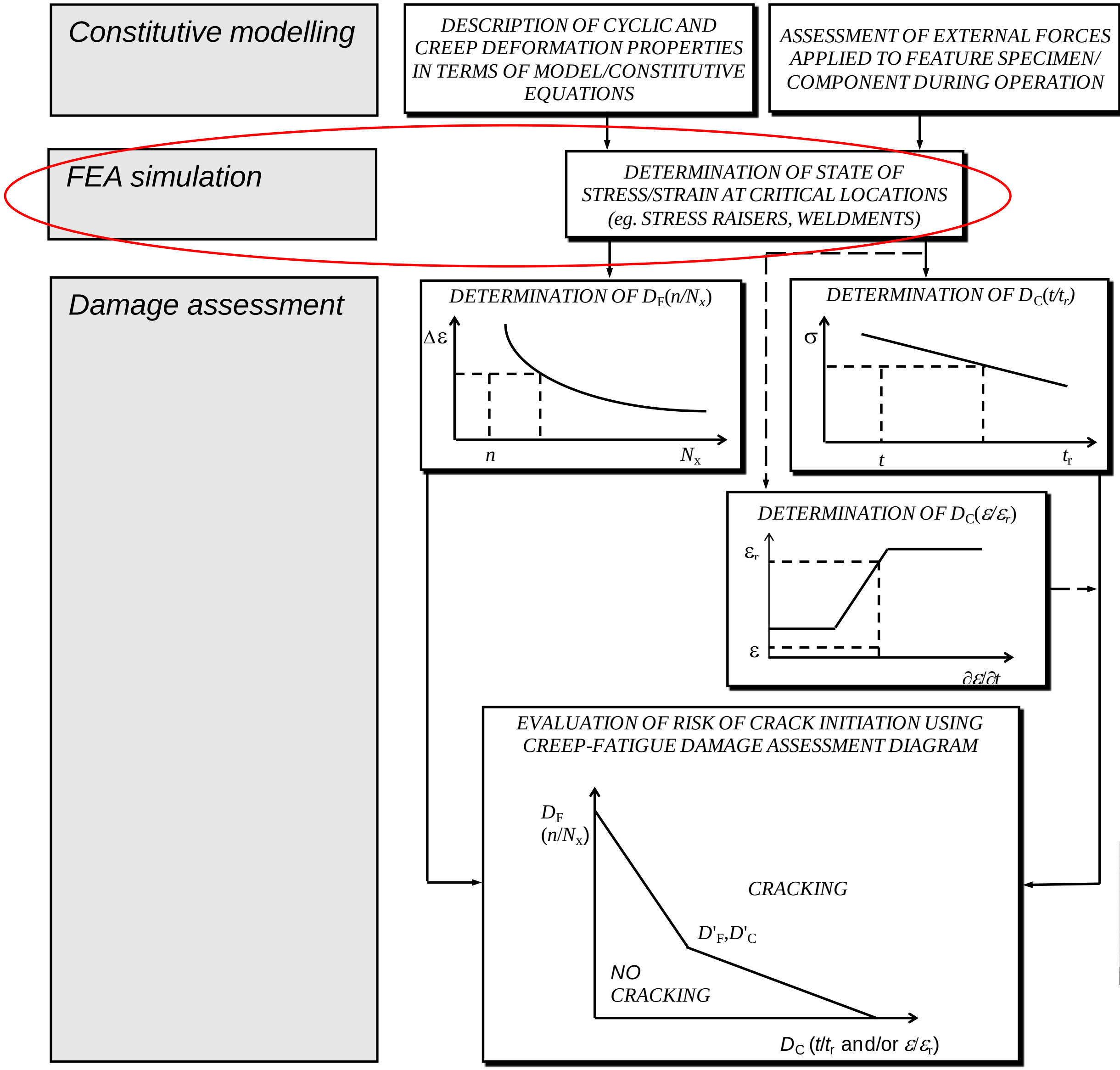
Constitutive deformation modelling

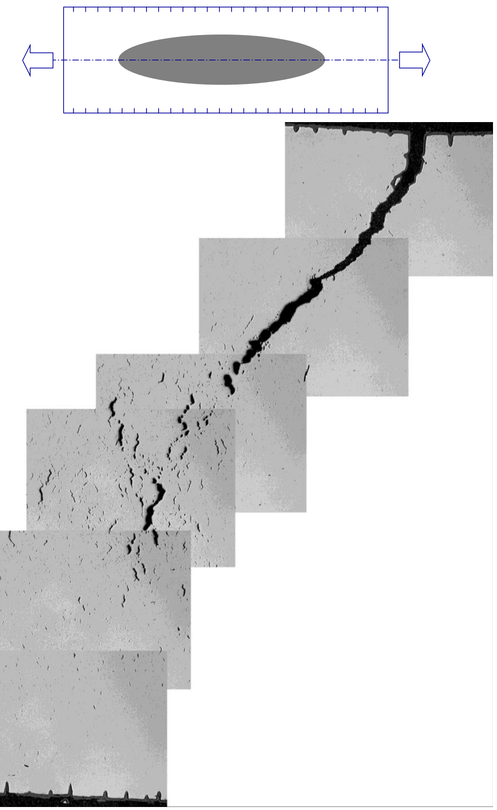
Representation of cyclic plasticity and creep deformation properties

- Constitutive modelling of cyclic-plasticity and creep
  - *Fixed-cycle or evolutionary response*
  - *Non-unified or unified modelling*
  - *Cast-to-cast variability*
  - *Material deformation (interaction) characteristics*

Creep-fatigue damage assessment

Generic flow diagram





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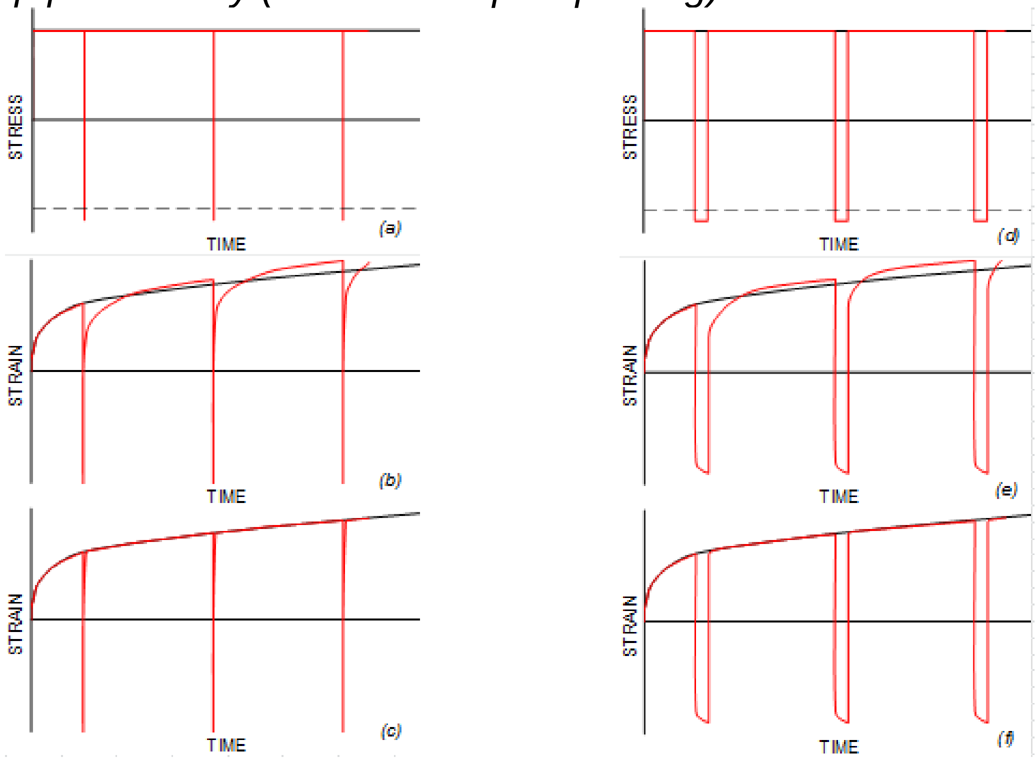
Cross-cutting issues relating to high temperature integrity

Determination of stress/strain state at critical location

- Issues to be considered as part of implementation of cyclic plasticity and creep deformation properties in (FEA) structural analysis
  - *Anelastic recovery (as an integral part of converting forward-creep to creep-relaxation response and vice-versa)*
  - *Primary creep persistency (PCP or creep re-priming)*



  - *FEA mesh optimisation to avoid mesh size sensitivity*

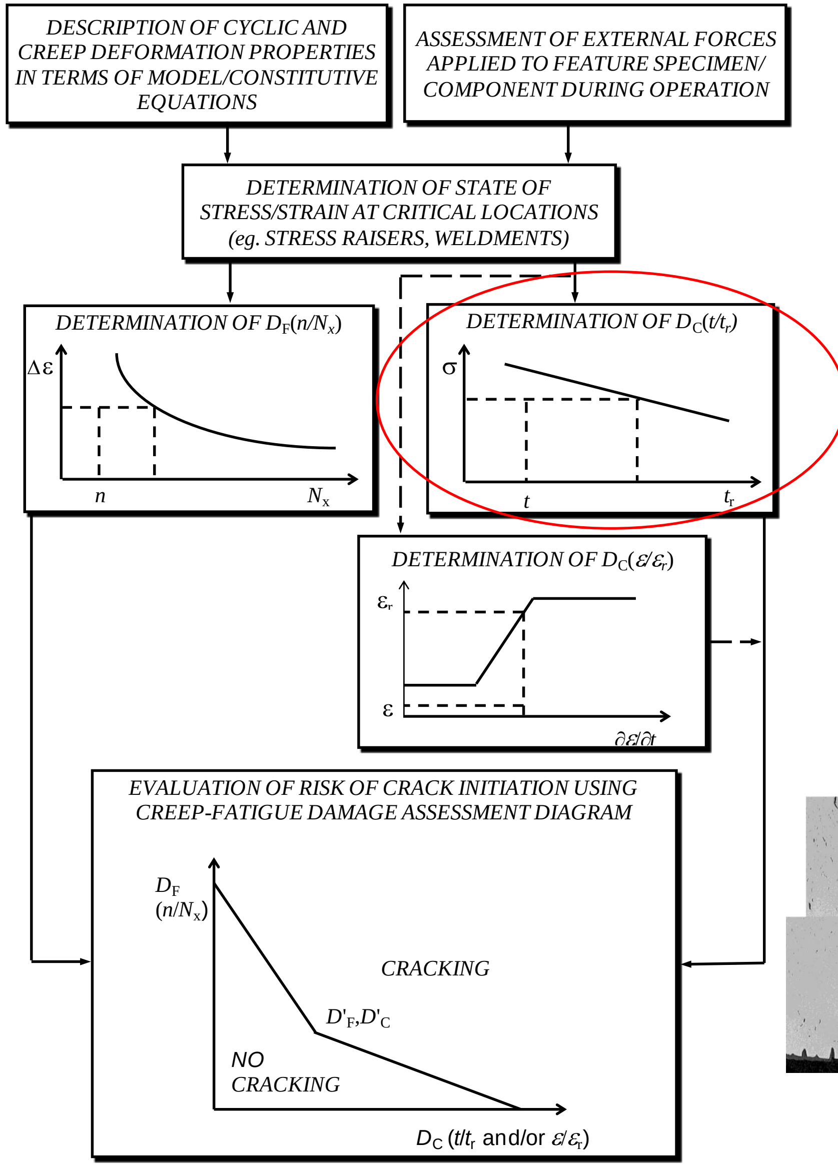
Creep-fatigue damage assessment

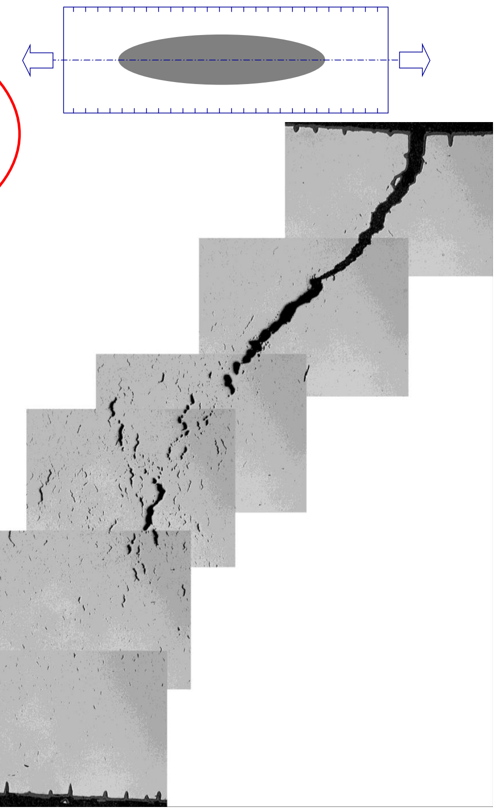
Generic flow diagram

Constitutive modelling

FEA simulation

Damage assessment





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LICON methodology

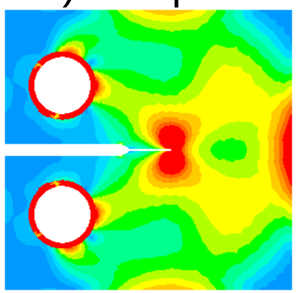
Model equations

- LICON method based on: ………………
  - where $\gamma \rightarrow \nu$ for σ_1-controlled rupture and $\gamma = 0$ for $\bar{\sigma}$-controlled rupture

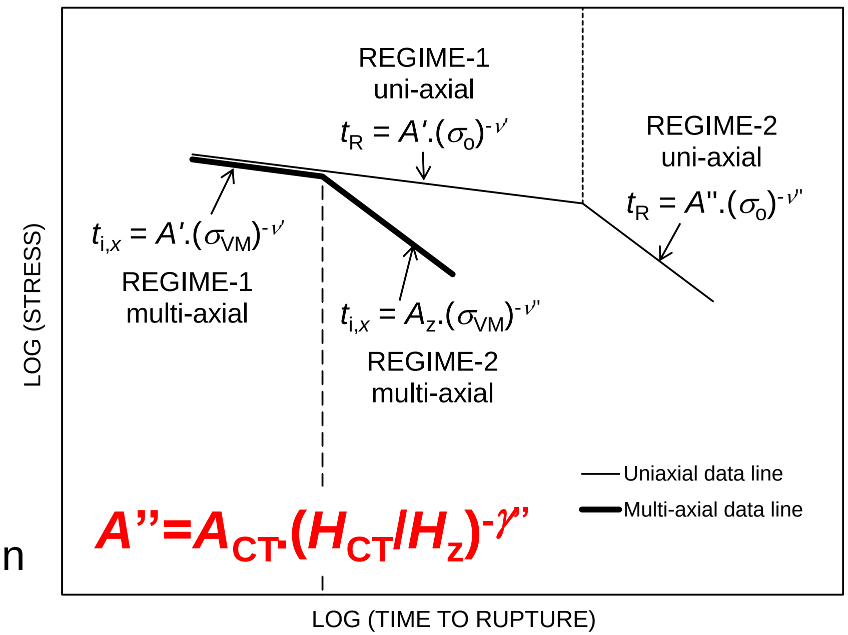
$$t_{\mathrm{i},x} = A(T).(\bar{\sigma})^{-\nu}.\left(\frac{\sigma_1}{\bar{\sigma}}\right)^{-\gamma}$$

- Working model equation (Regime-2) is:
  - where *H* is $\sigma_1/\bar{\sigma}_{\mathrm{VM}}$ ratio established for (steady state) creep conditions by FEA

$$t^{z}_{i,x} = A_{\mathrm{CT}}.(\bar{\sigma}_{\mathrm{VM}})^{-\nu''}.\left(\frac{H_{\mathrm{CT}}}{H_z}\right)^{-\gamma''}$$



  - H_{CT} is (steady-state) creep *H*-multiaxiality factor for CT testpiece
    - ➢ *CT testpiece found to be most effective in accelerating onset of grain/lath boundary cavitation damage (∴ adopted for LICON)*
  - H_Z is (steady-state) creep *H*-multiaxiality factor for structural feature under evaluation
    - ➢ *H_Z = 1 for uniaxial testpiece*
    - ➢ *H_Z determined by FEA for component features (and uniaxial weldment specimens)*



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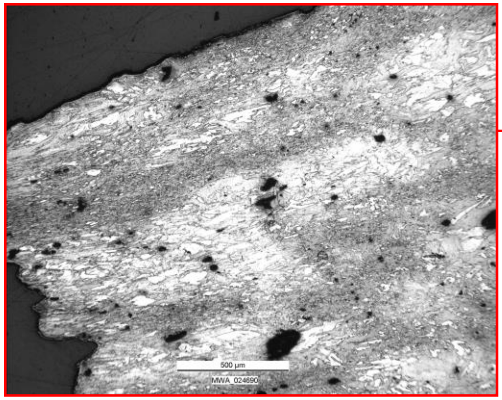
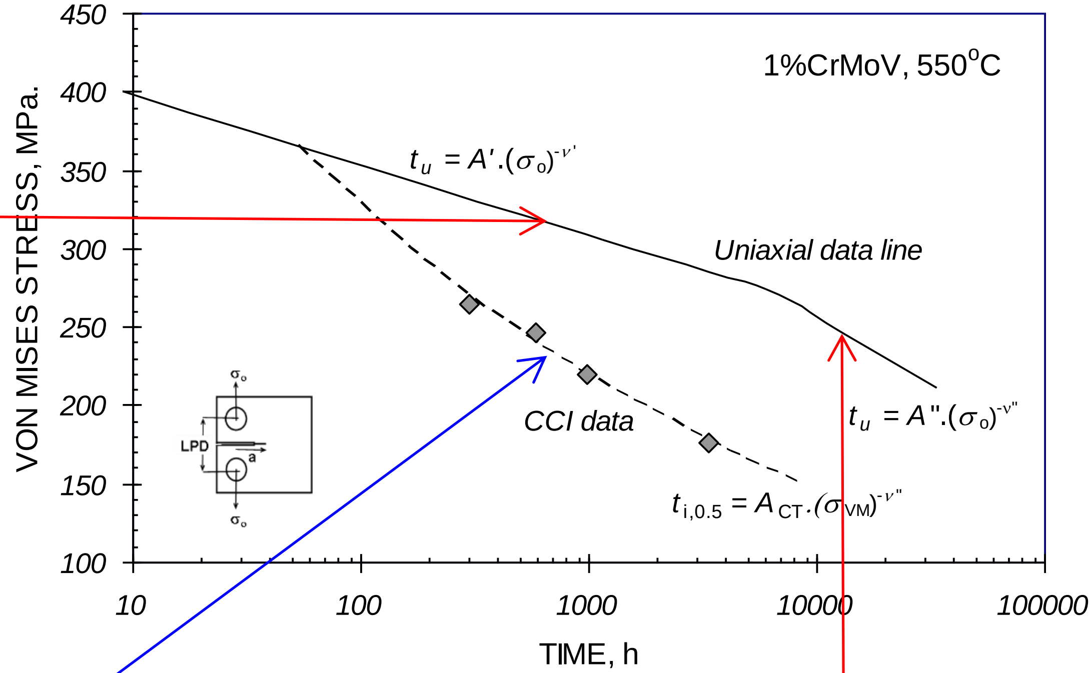
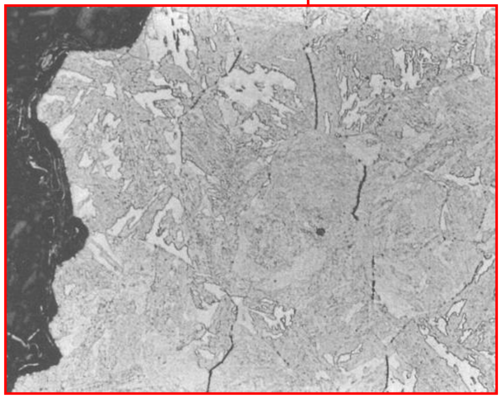
Creep crack initiation endurances

1CrMoV steel, 550°C

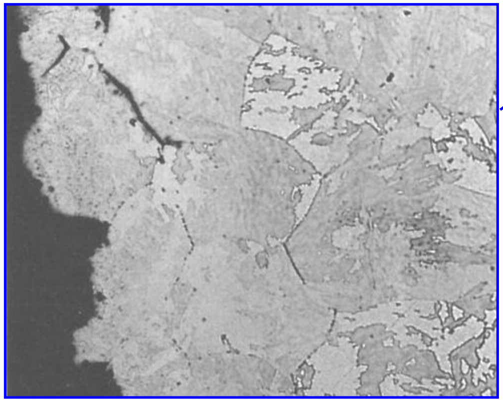


Regime-1 damage appearance





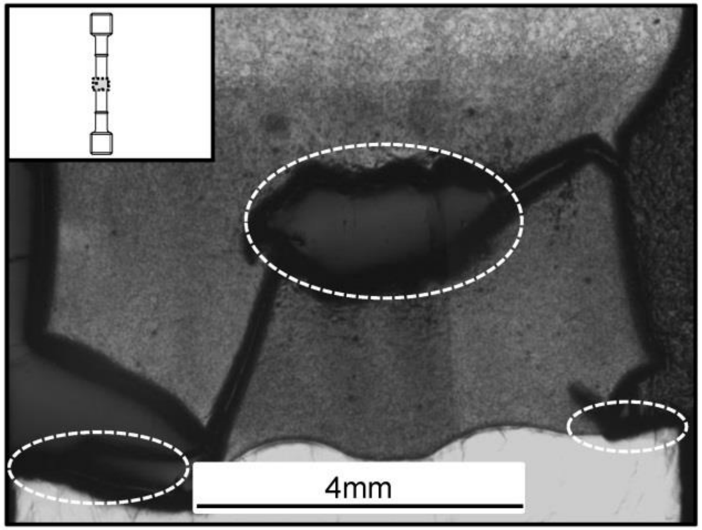
Regime-2 damage appearance in uniaxial testpieces in >10kh

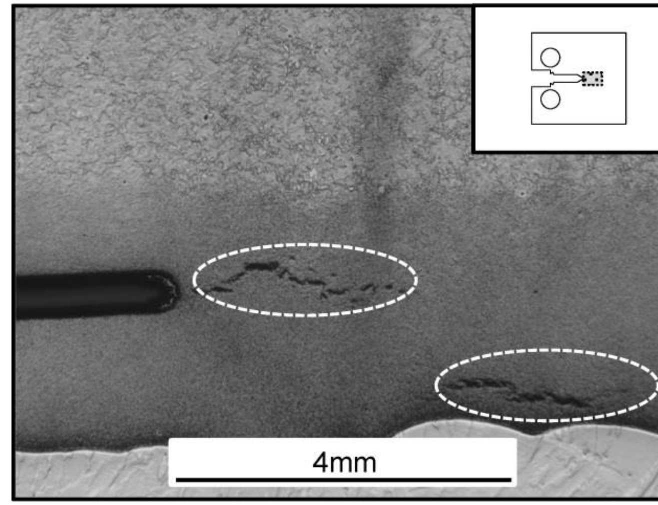


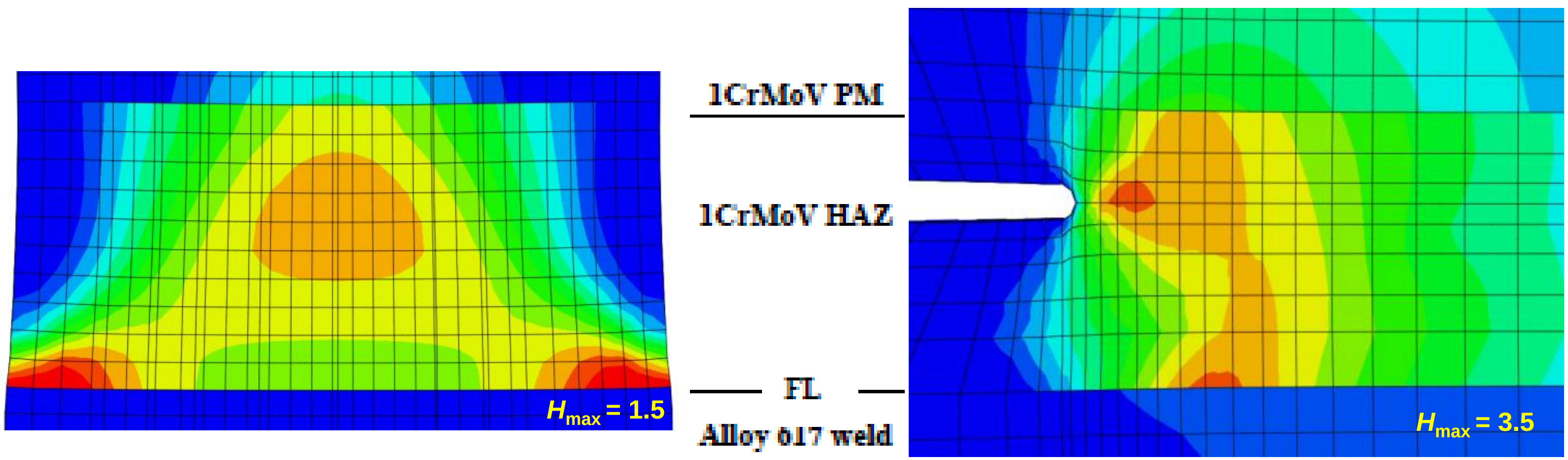
Regime-2 damage appearance at crack tip of CT testpiece in <1kh

LICON methodology – Dissimilar metal weld

Creep damage location predictions in uniaxial and CT specimens





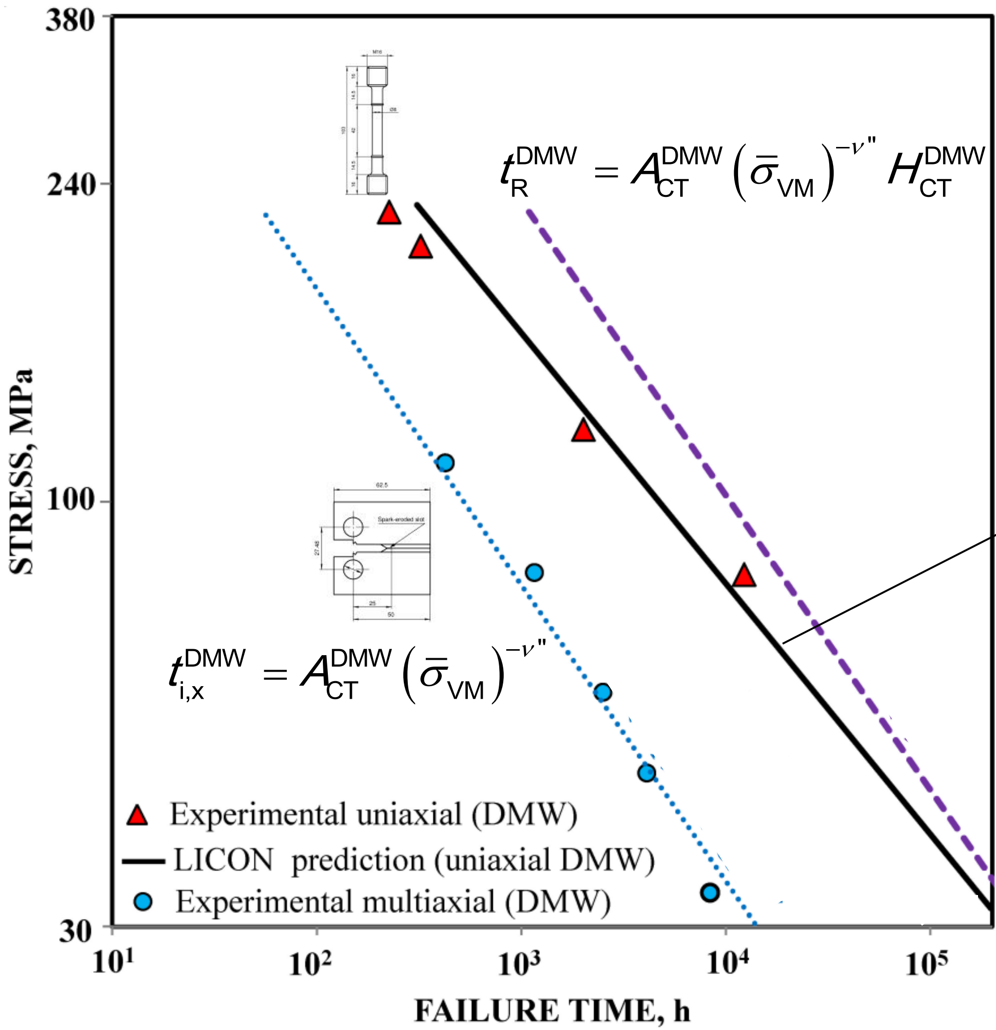


$$t_r = A^{"} \sigma_0^{-v^{"}} H_{DMW}^{-v^{"}}$$

E Hosseini, SR Holdsworth, E Mazza, 2013, Intern. J. Pressure Vessels & Piping

LICON methodology – Dissimilar metal weld

Prediction of uniaxial creep rupture data



$$t_{R}^{DMW} = A_{CT}^{DMW} \left(\bar{\sigma}_{VM}\right)^{-\nu''} \left(\frac{H_{CT}^{DMW}}{H_{uniaxial}^{DMW}}\right)^{-\nu''}$$

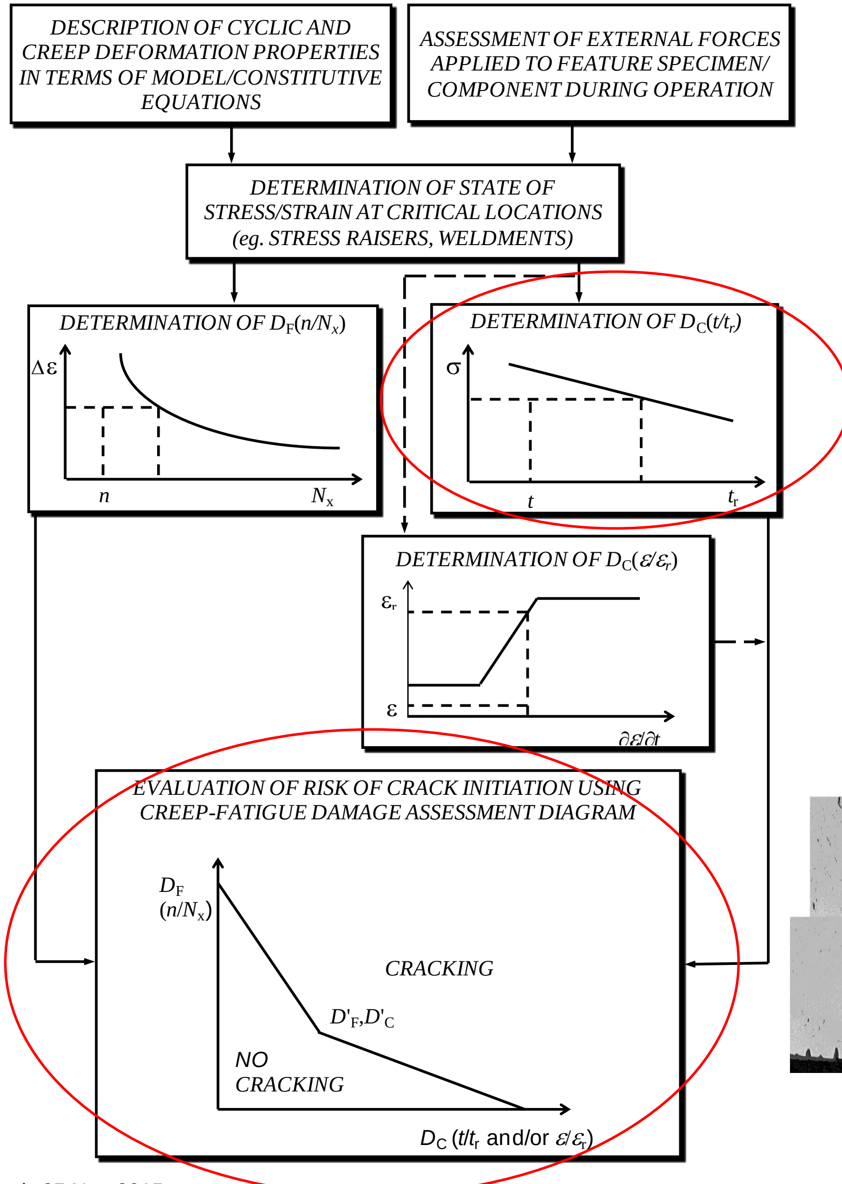
Creep-fatigue damage assessment

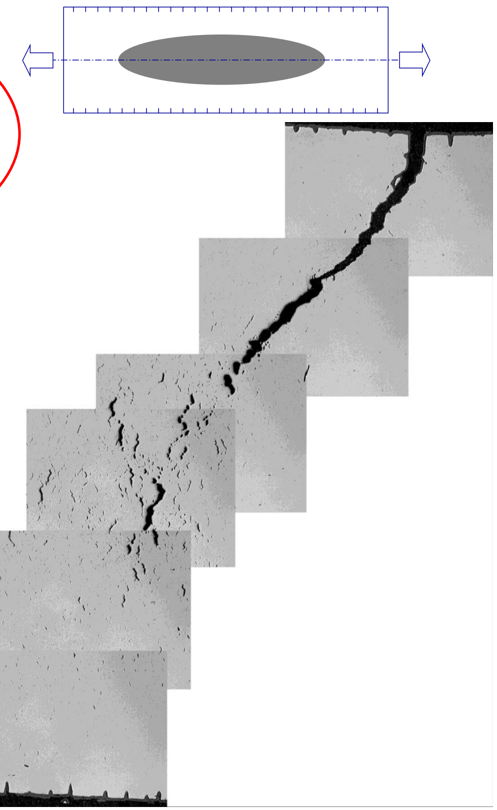
Generic flow diagram

Constitutive modelling

FEA simulation

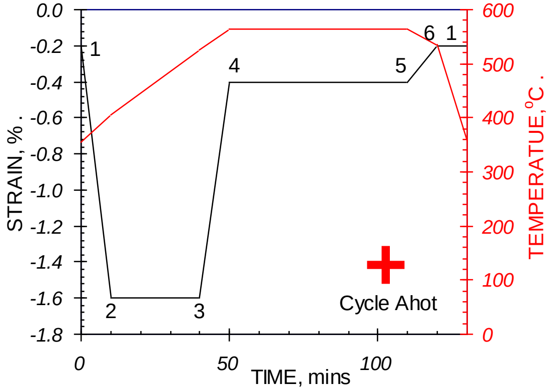
Damage assessment

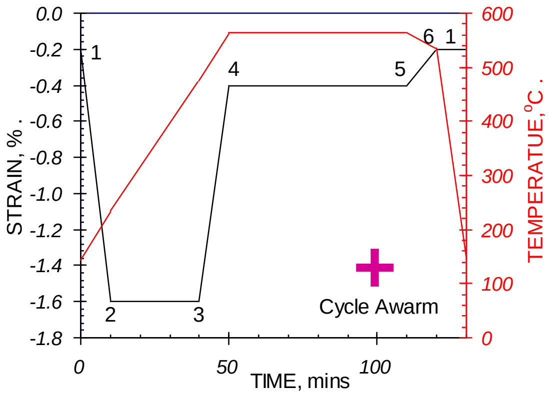


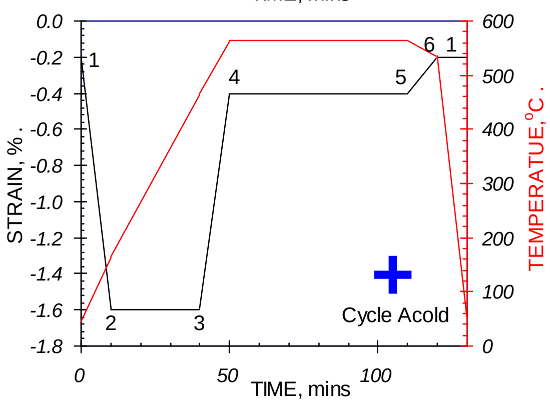


Creep-fatigue damage accounting

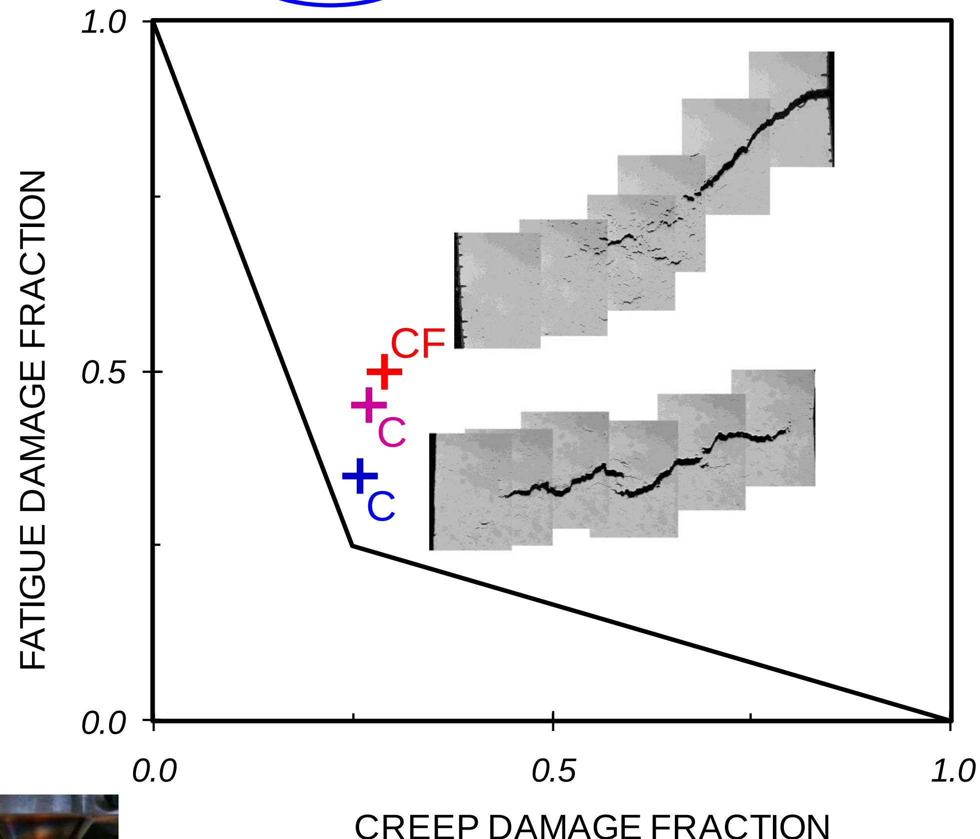
Assessment using conventional cyclic endurance and creep rupture properties in damage calculation (e.g. 1CrMoV steel at 565ºC)







$$D_{\mathrm{F}} = N_{\mathrm{CF}} / N_{\mathrm{LCF}}(\Delta\varepsilon)$$



$$D_{\mathrm{C(t)}} = N_{\mathrm{CF}} \int_0^{t_{\mathrm{h}}} dt / t_{\mathrm{R}}(\sigma_t)$$

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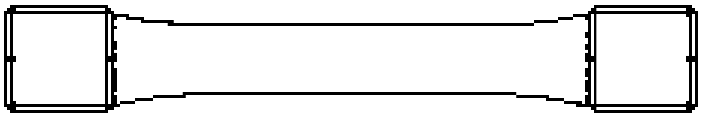
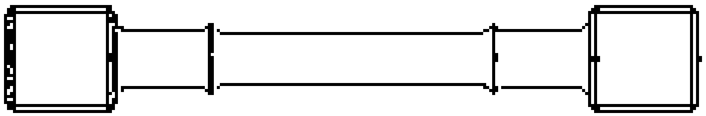
Influence of prior fatigue deformation on creep-rupture time

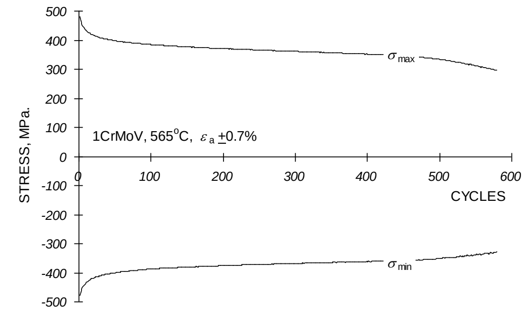
1CrMoV, 565°C

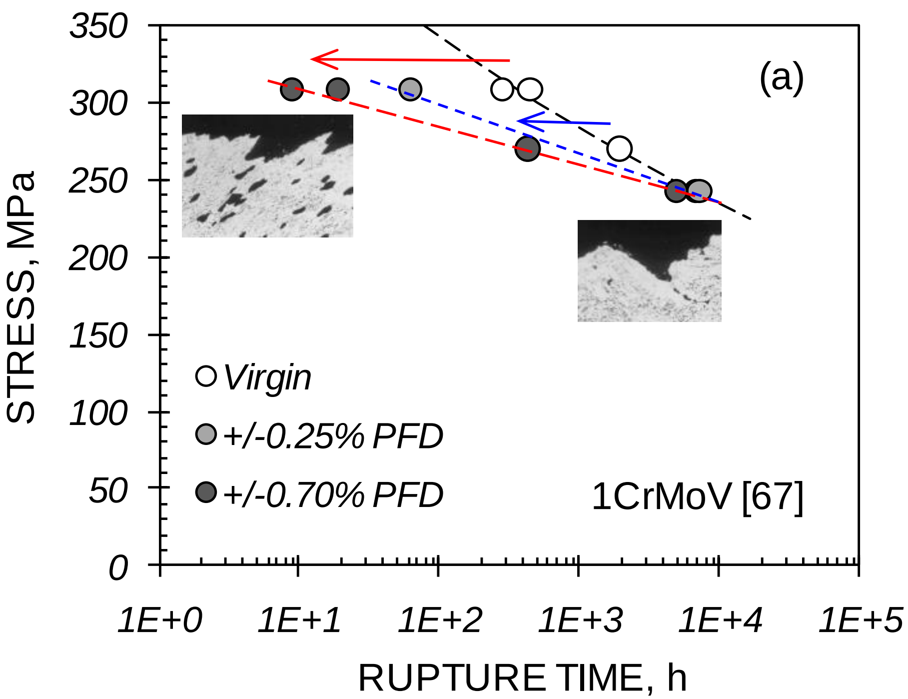


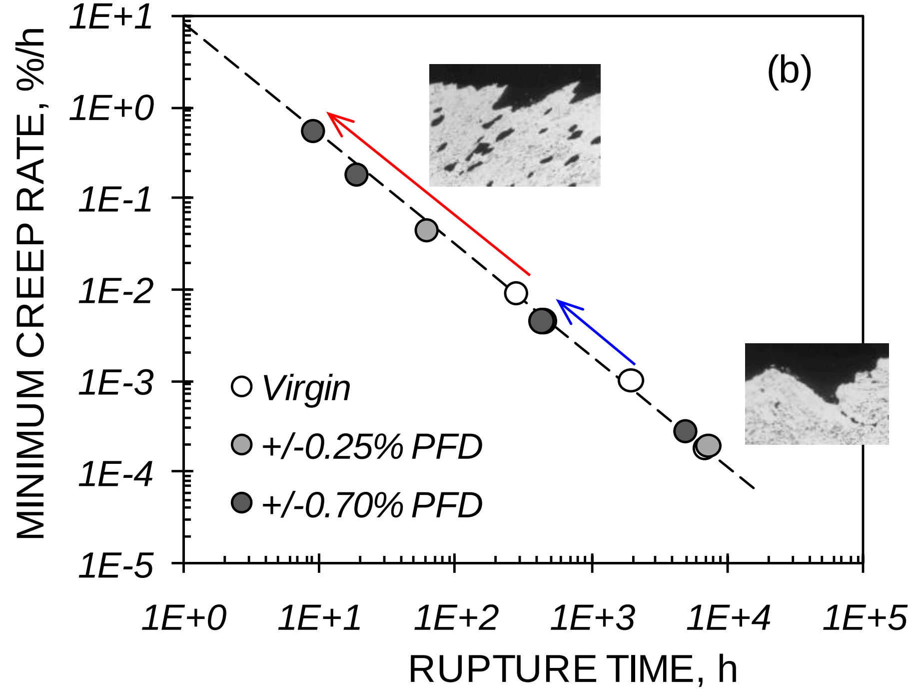
PFD to 0.5.N_i, d_o:10mm



Creep to rupture, d_o:8mm



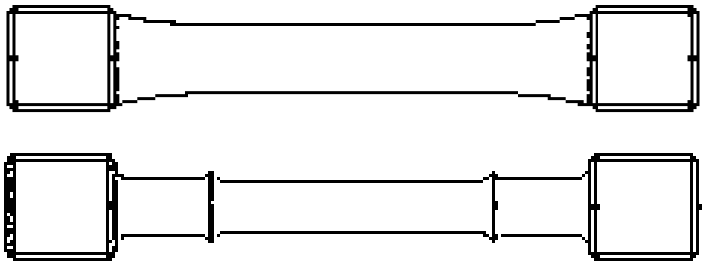




Binda et al, 2010

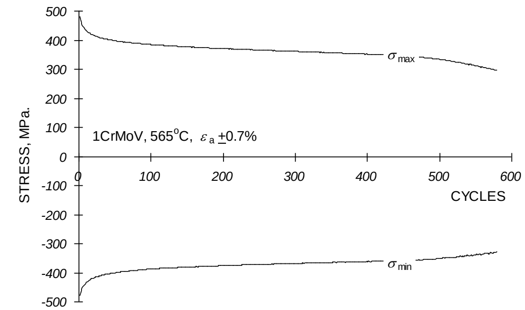
Influence of PFD on creep-rupture ductility

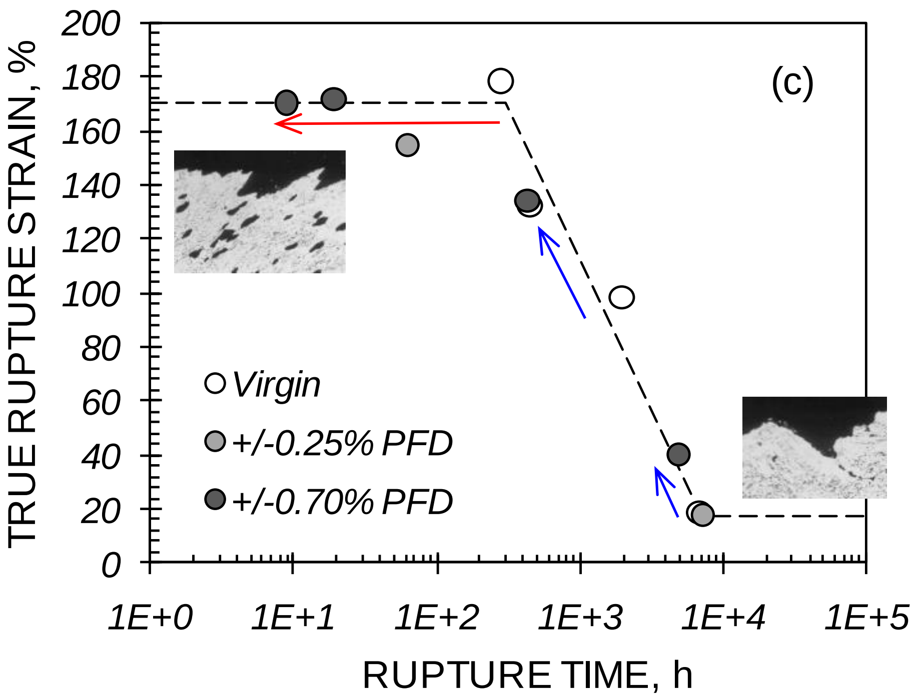
1CrMoV, 565°C

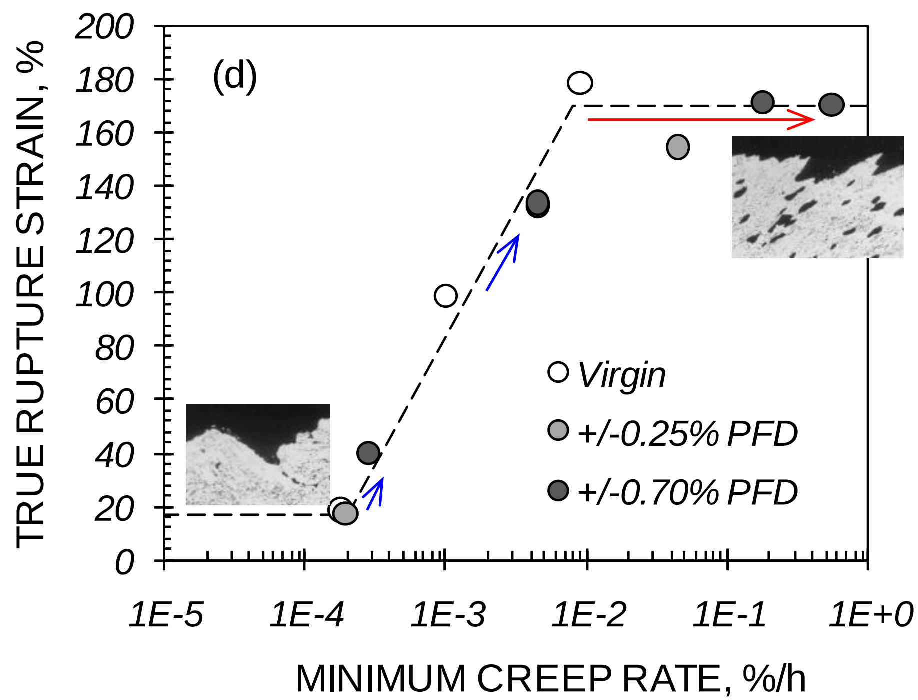


PFD to $0.5.N_i$, d_o:10mm

Creep to rupture, d_o:8mm



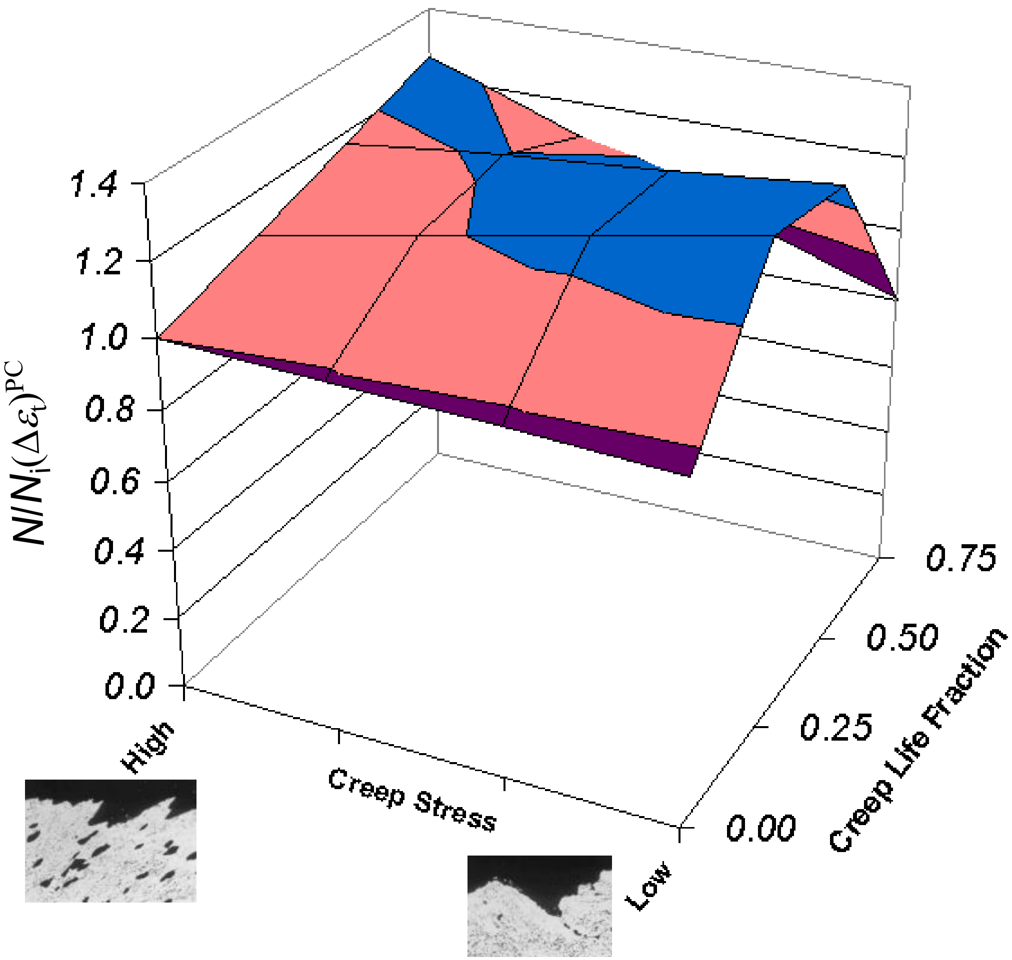




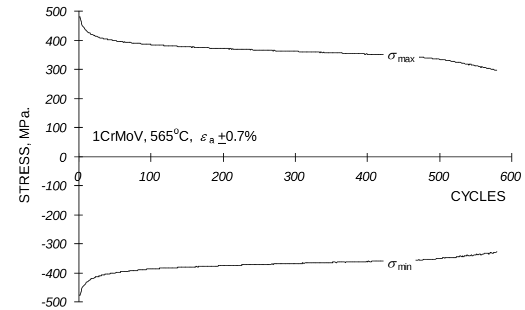
Binda et al, 2010

Influence of prior creep deformation on cyclic endurance

Dependence on creep loading stress (1CrMoV steel at 550^{o}C)



Based on results from Binda: after Shinya, Kyono, Kushima & Yokoi, Trans. NRIM, 1987, 29(2),115



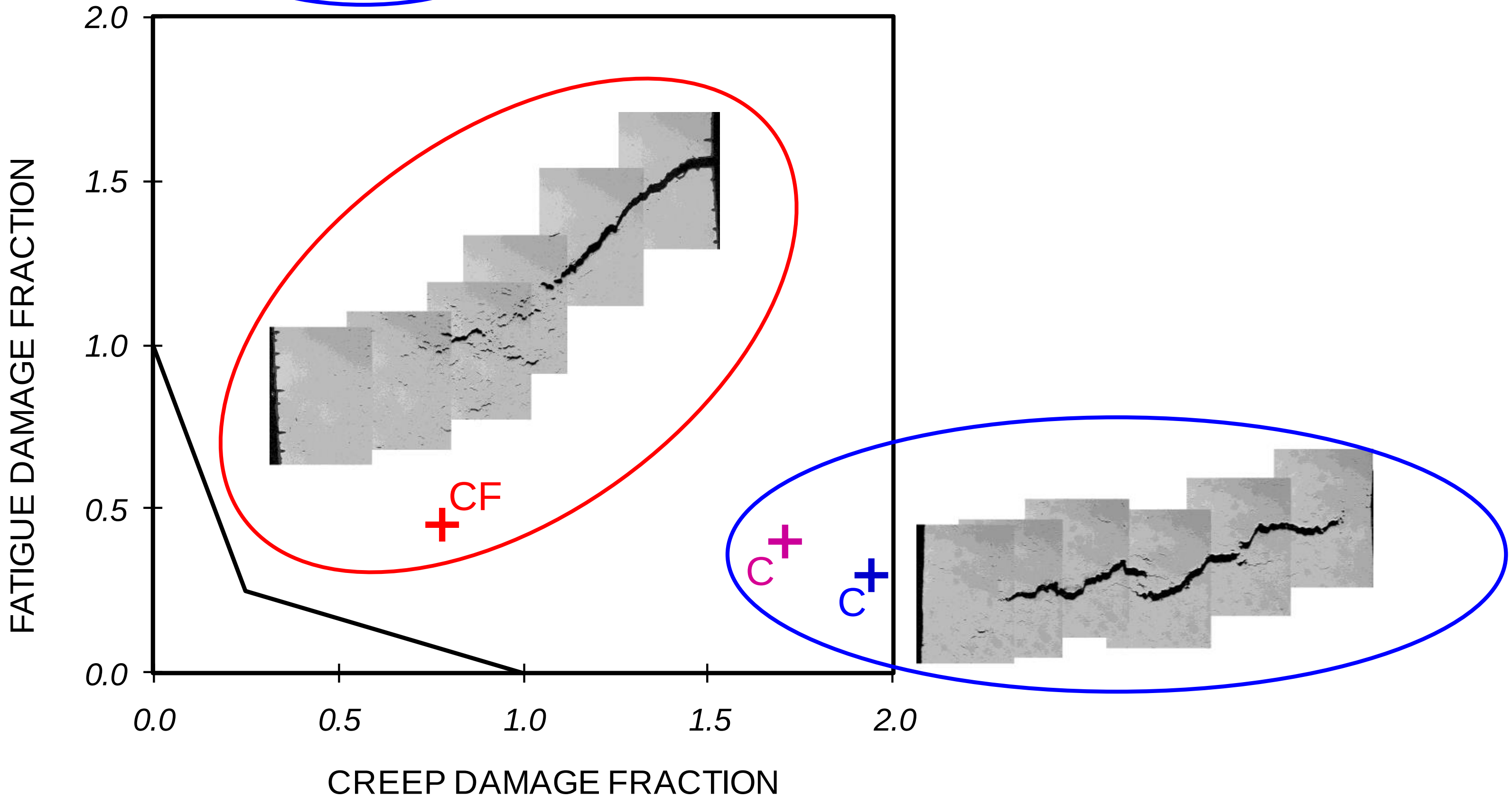
Reducing stress responsible for creep:

- Increasing time at temperature and increasing softening
- Damage mechanism change from:
  - *High ductility particle/matrix decohesion mode with no significant physical damage until close to the end of life*
  - *Low ductility grain boundary cavity development mode with significant damage developing at intermediate life fractions*

Creep-fatigue damage accounting

Assessment using prior deformation modified cyclic endurance and creep rupture properties in damage calculation (e.g. 1CrMoV steel at 565°C)

$$D_F^{PC} = N_{CF} / N_{LCF}(\Delta\varepsilon)^{PC}$$



$$D_C^{PF} = N_{CF} \int_0^{t_h} dt / t_R(\sigma_t)^{PF}$$

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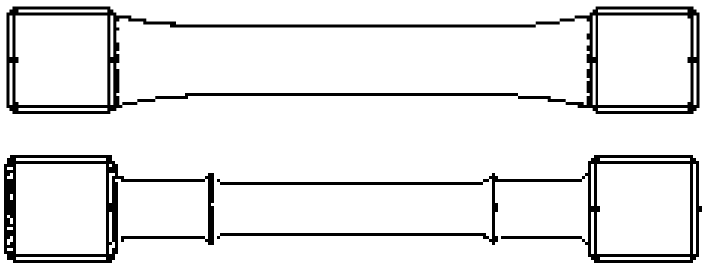
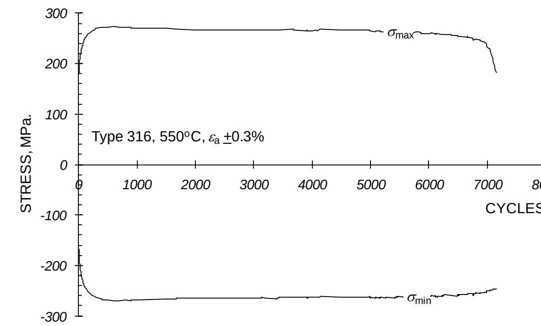
Influence of prior fatigue deformation on creep-rupture time

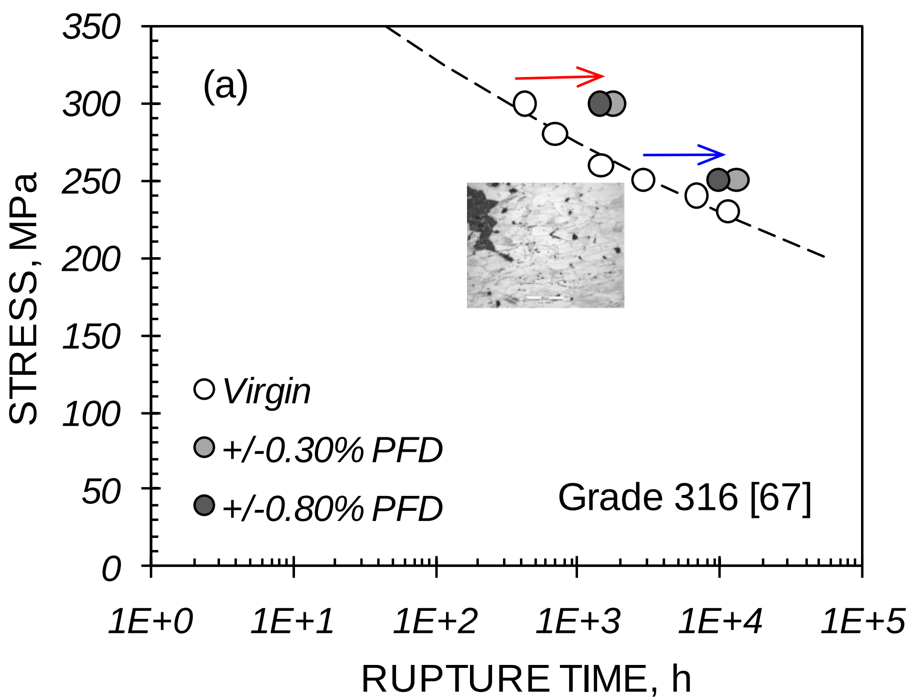
17Cr12Ni2Mo (TP316), 550^{o}C

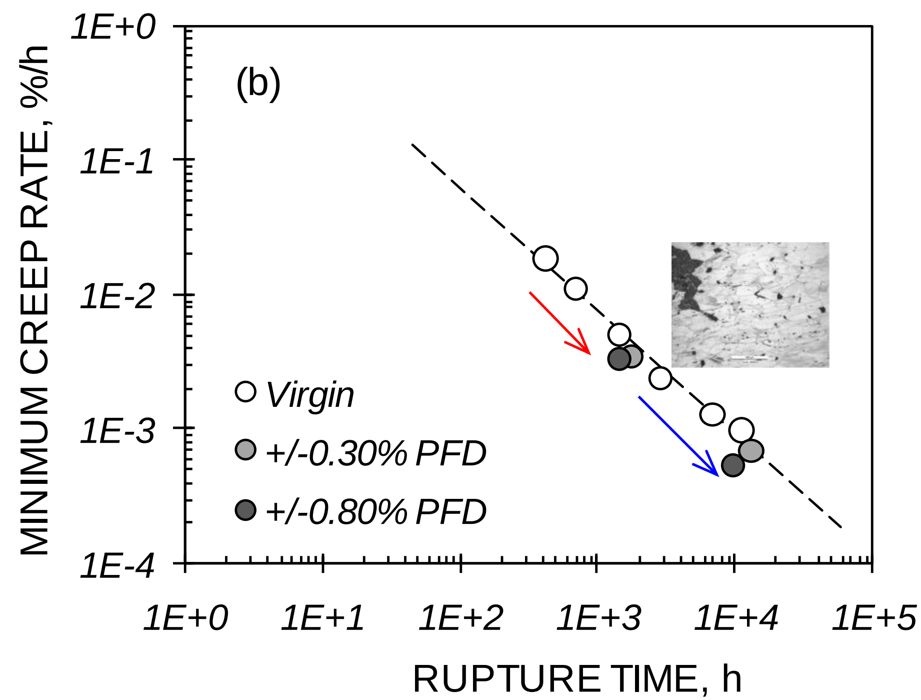


PFD to 0.1.N_i, d_o:10mm

Creep to rupture, d_o:8mm



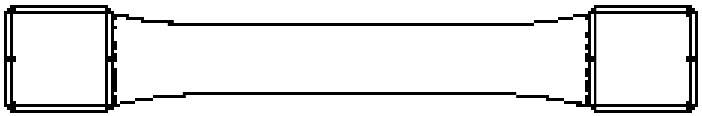




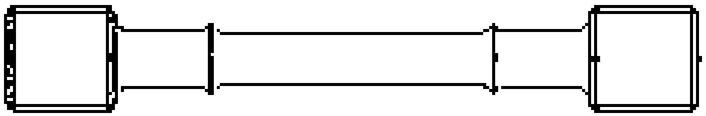
Binda, 2010

Influence of PFD on creep-rupture ductility

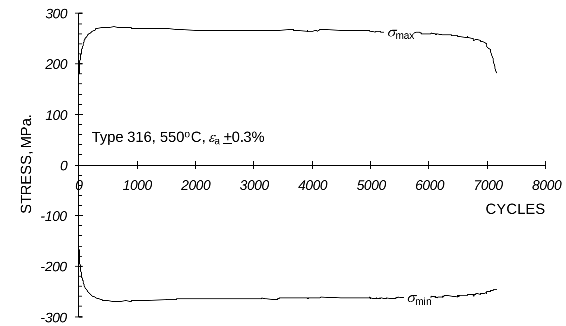
17Cr12Ni2Mo (TP316), 550^{o}C

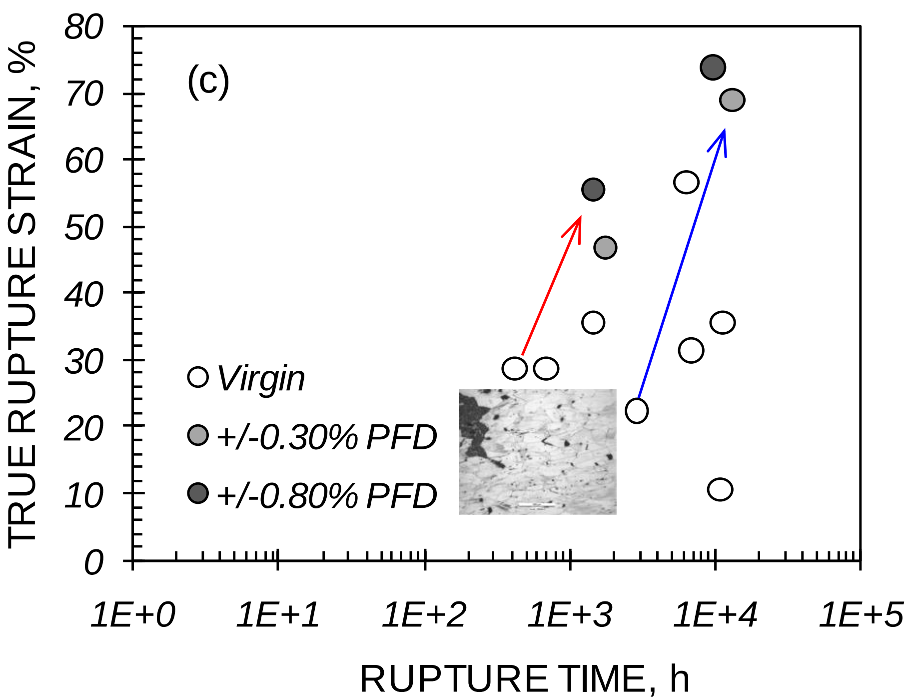


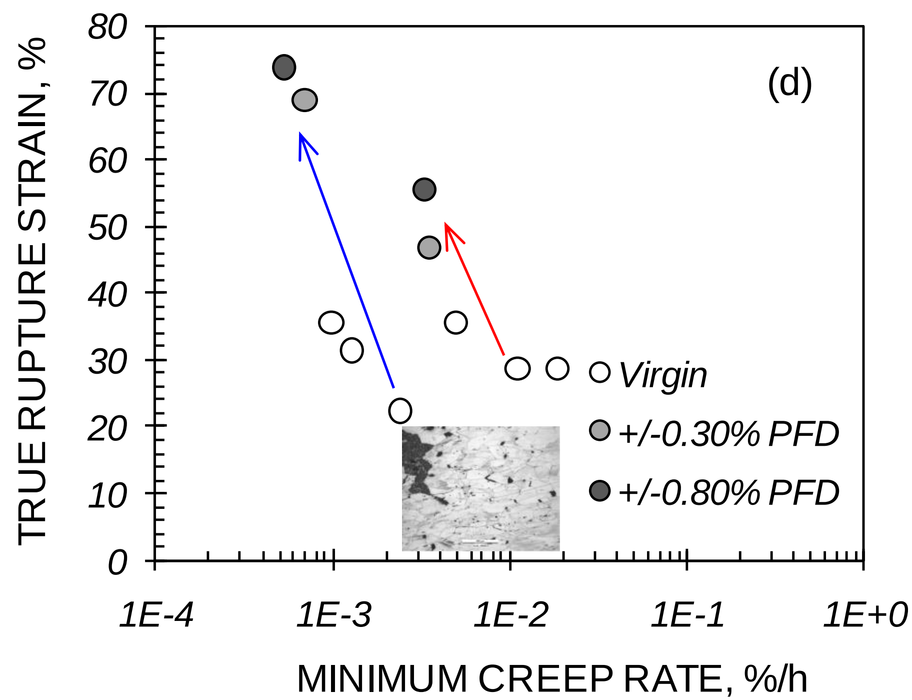
PFD to 0.1.N_i, d_o:10mm



Creep to rupture, d_o:8mm







Binda, 2010

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Cross-cutting issues relating to high temperature integrity
Concluding remarks

- Constitutive modelling of cyclic-plasticity and creep
  - *Fixed-cycle or evolutionary response*
  - *Non-unified or unified modelling*
  - *Cast-to-cast variability*
  - *Material deformation (interaction) characteristics*
  - *Importance of familiarity with material characteristics / deformation response*
- Determination of stress/strain state at critical locations
  - *Anelastic recovery, primary creep persistency*
  - *Importance of familiarity with material characteristics / deformation response*
- Damage assessment and summation
  - *Long time creep rupture strength properties from relatively short duration tests, LICON, a preliminary solution for new alloys and weldments*
  - *Representation of cyclic plasticity on creep, and vice versa*
  - *Importance of familiarity with material characteristics / deformation response*