Cross-Cutting Issues Relating to High Temperature Integrity

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High Temperature Integrity
Mechanical Integrity for Energy Systems
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

100kh CREEP-RUPTURE STRENGTH, MPa.

- Low alloy bainitic steels
- Advanced 10%Cr martensitic steels
- Weldable Ni base alloys (large sections)

MARBN?

Ni base alloy
10%Cr steel
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
  \[ D_F = 1 - D_C \cdot (1 - D_F')/D_C \]
  for \( D_C < D_C' \)
  \[ D_F = [1 - D_C]D_C'/(1 - D_C) \]
  for \( D_C > D_C' \)

Evaluation of risk of crack initiation using creep-fatigue damage assessment diagram
Creep-fatigue damage assessment

Generic flow diagram

Constitutive modelling

FEA simulation

Damage assessment

DESCRIPTION OF CYCLIC AND CREEP DEFORMATION PROPERTIES IN TERMS OF MODEL/CONSTITUTIVE EQUATIONS

ASSESSMENT OF EXTERNAL FORCES APPLIED TO FEATURE SPECIMEN/COMPONENT DURING OPERATION

DETERMINATION OF STATE OF STRESS/STRAIN AT CRITICAL LOCATIONS (eg. STRESS RAISERS, WELDMENTS)

DETERMINATION OF $D_F(n/N_x)$

DETERMINATION OF $D_C(t/t_r)$

DETERMINATION OF $D_C(e/e_r)$

EVALUATION OF RISK OF CRACK INITIATION USING CREEP-FATIGUE DAMAGE ASSESSMENT DIAGRAM

EMPA, SRH|MatISSEholdsworth.pptx, JRC (Petten), 25.Nov-2015
Response to strain-controlled LCF cycles
Cyclic softening (1CrMoV, 565°C), cyclic hardening (TP316, 550°C)
Cross-cutting issues relating to high temperature integrity

Representation of cyclic plasticity and creep deformation properties

- **Cyclic plasticity (non-unified or unified)**

  \[ \varepsilon_p = \int_0^t \sqrt{\frac{2}{3} \sum_i \sum_j \varepsilon_{p,ij} \cdot \varepsilon_{p,ij}} \cdot \vartheta \]

  \[ \sigma = \frac{C_k}{\gamma_k} \left( 1 - e^{-\gamma \varepsilon_p} \right) + \sigma_o \]

  \[ \dot{\alpha}_{k,ij} = C_k \dot{\varepsilon}_p \left( \frac{\sigma_{ij} - \alpha_{ij}}{\sigma_o} \right) - \gamma_k \alpha_{k,ij} \dot{\varepsilon}_p + \frac{\alpha_{k,ij}}{C_k} \dot{\varepsilon}_k \]

  \[ f = J_2 (\sigma - \alpha) = \sigma_o \]

- **Creep (non-unified)**

  \[ \varepsilon_C = A \sigma^n t^p + \dot{\varepsilon}_{C,\text{min}} t \]

  \[ \varepsilon_C = \frac{\varepsilon_D (R_R/R_D - 1)}{[R_R/\sigma_D - 1]} = \frac{\varepsilon_C}{R_R/\sigma - 1} \]

  - 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

Constitutive modelling → FEA simulation → Damage assessment

**Constitutive modelling**
- DESCRIPTION OF CYCLIC AND CREEP DEFORMATION PROPERTIES IN TERMS OF MODEL/CONSTITUTIVE EQUATIONS

**FEA simulation**
- ASSESSMENT OF EXTERNAL FORCES APPLIED TO FEATURE SPECIMEN/COMPONENT DURING OPERATION

**Damage assessment**
- DETERMINATION OF STATE OF STRESS/STRAIN AT CRITICAL LOCATIONS (e.g., STRESS RAISERS, WELDMENTS)
- EVALUATION OF RISK OF CRACK INITIATION USING CREEP-FATIGUE DAMAGE ASSESSMENT DIAGRAM

- CRACKING
- NO CRACKING
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

DESCRIPTION OF CYCLIC AND CREEP DEFORMATION PROPERTIES IN TERMS OF MODEL/CONSTITUTIVE EQUATIONS

ASSESSMENT OF EXTERNAL FORCES APPLIED TO FEATURE SPECIMEN/COMPONENT DURING OPERATION

DETERMINATION OF STATE OF STRESS/STRAIN AT CRITICAL LOCATIONS (eg. STRESS RAISERS, WELDMENTS)

DETERMINATION OF $D_F(n/N_x)$

DETERMINATION OF $D_C(\varepsilon_{\text{eff}})$

DETERMINATION OF $D_C(t/t_r)$

EVALUATION OF RISK OF CRACK INITIATION USING CREEP-FATIGUE DAMAGE ASSESSMENT DIAGRAM

$D_F(n/N_x)$

$D_C(t/t_r)$ and/or $D_C$
LICON methodology

**Model equations**

- **LICON method based on:** …………
  - where $\gamma \rightarrow \nu$ for $\sigma_1$-controlled rupture and $\gamma = 0$ for $\overline{\sigma}$-controlled rupture

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

  \[ t_{i,x} = A(T).(\overline{\sigma})^{-\nu}.\left(\frac{\sigma_1}{\overline{\sigma}}\right)^{-\gamma} \]

  \[ t^z_{i,x} = A_{CT}.(\overline{\sigma}_{VM})^{-\nu''}.\left(\frac{H_{CT}}{H_{Z}}\right)^{-\gamma''} \]

- $H_{CT}$ 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)
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

\[ t_r = A' \sigma_0^{-\nu} H_{DMW}^{-\nu} \]


LICON methodology – Dissimilar metal weld
Prediction of uniaxial creep rupture data

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

\[ t_{i,x}^{DMW} = A_{CT}^{DMW} \left( \bar{\sigma}_{VM} \right)^{-\nu''} \left( \frac{H_{CT}^{DMW}}{H_{uniaxial}^{DMW}} \right)^{-\nu''} \]
Creep-fatigue damage assessment

Generic flow diagram

Constitutive modelling

- Description of cyclic and creep deformation properties in terms of model/constitutive equations
- Assessment of external forces applied to feature specimen/component during operation

Damage assessment

- Determination of state of stress/strain at critical locations (e.g., stress raisers, weldments)
- Determination of $D_F(n/N_x)$
- Determination of $D_C(t/t_r)$
- Determination of $D_C(e/e_r)$

FEA simulation

- Constitutive modelling
- Damage assessment

Evaluations of risk of crack initiation using creep-fatigue damage assessment diagram
Creep-fatigue damage accounting
Assessment using conventional cyclic endurance and creep rupture properties in damage calculation (e.g. 1CrMoV steel at 565°C)

\[
D_F = \frac{N_{CF}}{N_{LCF}(\Delta)}
\]

\[
D_c(t) = N_{CF} \int_{0}^{\tau} dt / t_R(\sigma(t))
\]
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

**Diagram (a):**
- **Minimum creep rate vs. rupture time:**
  - **Virgin**
  - +/-0.25% PFD
  - +/-0.70% PFD

**Diagram (b):**
- **Stress vs. rupture time:**
  - **1CrMoV, 565°C, \(e_a + 0.7\%\)**
  - Creep to rupture, \(d_o\):8mm

*Binda et al, 2010*
Influence of PFD on creep-rupture ductility

1CrMoV, 565°C

PFD to 0.5 \( N_i \), \( d_o:10\)mm

Creep to rupture, \( d_o:8\)mm

TRUE RUPTURE STRAIN, %

RUPTURE TIME, h

Virgin

\ (+/-0.25\% \ PFD \)

\ (+/-0.70\% \ PFD \)

Binda et al, 2010
Influence of prior creep deformation on cyclic endurance
Dependence on creep loading stress (1CrMoV steel at 550°C)

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

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

\[ D^\text{PC}_F = \frac{N_{CF}}{N_{LCF}(\Delta \varepsilon)^\text{PC}} \]

\[ D^\text{PF}_C = N_{CF} \int_0^{t_h} \frac{dt}{t_R(\sigma_t)^\text{PF}} \]
Influence of prior fatigue deformation on creep-rupture time

$17\text{Cr}12\text{Ni}2\text{Mo (TP316), 550°C}$

PFD to $0.1.N_i$, $d_0$:10mm

Creep to rupture, $d_0$:8mm

Virgin $\pm 0.3\%$ PFD
Virgin $\pm 0.80\%$ PFD

Grade 316 [67]

Binda, 2010
Influence of PFD on creep-rupture ductility
17Cr12Ni2Mo (TP316), 550°C

PFD to 0.1\(N_i\), \(d_o:10\)mm

Creep to rupture, \(d_o:8\)mm

Binda, 2010
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