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Supporting legislation

Advances in high temperature property determination for Gen-IV materials

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Background

Commercially available steels (like 316L, 316L(N) and P91) have to be used for the near future ESNII GenIV reactors.

Challenge:
The service temperatureseloads for the ESNII Gen-IV test reactors are mainly in the low temperature and low stress regime where creep properties are rarely generated

- **Industrial main interest lies in the high temperature / high stress regime**

Objectives:

Design for creep can be avoided by service temperature / time below negligible creep temperature ($T_{NEC}$) ...

Simpler methodologies to determine Creep-Fatigue life with and without the interaction diagram ...

- **Improved methodologies for creep-fatigue interaction,**
- **Impact of softening on relaxation behaviour**
- **Relaxation extrapolation**
Supporting Projects

EU project MATTER
• Properties for P91 steel, 3 heats (MATTER, DEMETRA, INTEGRITY)
• Defining low stress/low temperature creep strain rates
• Definition of $T_{\text{NEC}}$ + new methodology (based on Wilshire Eq.)
• Spin-off: curves for EN-13445 (unfired pressure vessels)
• Simplified CF models compared to SOTA models (Interaction Diagram)

EU project MATISSE
• models for cyclic-softening and impact on CF damage (P91)
• models for creep-fatigue crack propagation

JRC internal projects MaCoSYMA & PreMaQ
• Standardization and support for CEN/TC54-WG59
• Development of a standard for Small Punch Testing

EERA-JPNM Pilot Project TASTE
• Test methods for determining material properties for thin walled tubes (fuel claddings)
$T_{NEC}$ curve (definition for EN-13445 revision)

MATTER: Grade 91, RCC-MRx reference stress $0.56 \cdot R_m \left( 1.5 \cdot 1/2.7 \cdot R_m \right)$
EN-13445 revision, reference stress $2/3 \cdot R_{p02}$
## EN-13445:2 steels
(curves suggested to WG59 creep for review)

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<th>Steel name</th>
<th>( T_{\text{min}} ) (°C)</th>
<th>( T_{\text{max}} ) (°C)</th>
<th>( \sigma_{\text{min}} ) (MPa)</th>
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= PROPOSED Probationary Phase (SECT III, Tome 6)  
= POTENTIAL Technical Appendix (SECT III, Tome 1)
EN-13445:7 creep resistant steels ongoing assessment work for CEN/TC54-WG59

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Challenges remain in defining the appropriate reference stress / rupture time correction factor

RCC-MRx
T_{NEC} curves exists for: 316L and 316L(N)
Methodology using Wilshire equation

\[
\frac{\sigma_{u/t/T}}{R_m} = \exp\left[-k(t_r \cdot \exp\left(-\frac{Q}{R \cdot T}\right))^u\right] \quad \text{or} \quad \frac{\sigma_{u/t/T}}{A \cdot R_{p02}} = \exp\left[-k(t_r \cdot \exp\left(-\frac{Q}{R \cdot T}\right))^u\right]
\]

\[
t_{\text{NEC}} = t_{\varepsilon \%} \quad \text{or} \quad t_{\text{NEC}} = \frac{t_r}{RTF}
\]

\[
T_{\text{NEC}} = \frac{Q}{R \cdot \ln\left(t_{\text{NEC}} \cdot \left[-\frac{1}{k} \ln\left(\frac{2}{3 \cdot A}\right)\right]^{-\frac{1}{u}}\right)}
\]

In MATTER, \(t_{\text{NEC}}\) was based on time to 0.2% creep strain

Creep strength tables EN10028:2,7 for \(\sigma_{u/t/T}\)
Example: 10CrMo910 (P22)

The reference stress \((2/3 \, R_{p02})\), equal to allowable stress, is the horizontal line at 0.27 normalized stress and the cross hairs on the RTF corrected rupture curve defines the location where the \(T_{\text{NEC}}\) curve is calculated.
**Time factors, Rupture and Strain (1%)**

Assessing the safety margin between the $t_{NEC}$ and the time to 1% creep strain $t_{1\%}$ for steel 10CrMo910.

*RTF=1000 and STF=240

*RTF=1000 from MATTER / time to reach 0.2% strain for P91 (T=375-550°C)
Time factors, weld strength reduction by 1.25 and 1.5

Assessing the safety margin between the $T_{\text{NEC}}$ curve and the corrected reduced rupture times with WCSRF=1.25 and 1.5 for steel 10CrMo910 steel.

The $\text{WTF}_{1.25} = 377$, $\text{WTF}_{1.5} = 143$, RTF=1000
Inversely $T_{NEC}$ curves for welds using strength reduction by 1.25 and 1.5

"The same procedure defined for base materials applies with the following modification: if the values of are different from those of the base materials, these values are to be multiplied by the relevant Weld Creep Strength Reduction Factor defined in 19.6."
Pending work for NEC

$T_{\text{NEC}}$ calculations for all creep resistant steels of EN10028-7 (for TC54/WG59)

- $\sigma_{\text{ref}} = \frac{2}{3} \cdot R_{p1\%}$ or $\sigma_{\text{ref}} = \frac{1}{3} \cdot R_m$ (1% proof or UTS)
- $T_{\text{NC}} = 425^\circ C$
- Additional curves for 316L and 316 L(N) using ECCC creep data sheets

**EN-10028:7 steels**

X3CrNiMoBN17-13-3 (316-LNB) and X6CrNi18-10 (304H) can be compared to

**RCC-MRx** $T_{\text{NEC}}$ curves for

- X2CrNiMo17-12-2 (316L), X6CrNi18-10 (304H) and X2CrNiMo17-12-2(N) (316L(N))

Sect.III, Tome1, Z, Appendix A3-1S, 2S and 3S
Predicting Creep-Fatigue life

In **MATTER** the P91 CF endurance (cycles to failure) was predicted by 3 methods

1. CF interaction diagram (RCC-MRx, R5 or ASME III-NH) with creep damage from the relaxation (life fraction or ductility exhaustion)
2. Simple LCF models with correction for creep strain accumulation, i.e increased total strain range $\Delta\varepsilon$ by relaxed strain or forward creep strain (at $N_{f/2}$)
3. Simplified models based on **reference stress** and hold time $t_h$, softening/hardening or strain range corrections not necessary

- The simplified models were the most robust/accurate and showed potential for design rule application ...
Examples of model predictions (P91 CF data set)

Simplified CF models (Manson-Halford and $\Phi$-model) vs EMDE and SMDE
(JRC, VTT, ANSTO paper*)

The calculated $Z$ values for the different models applied on the same data set (strain controlled tests and 550°C). The test with the longest hold time is encircled.

*Holmstrom S., Pohja R., Payten W., Creep-Fatigue Interaction Models for Grade 91 Steel, ASTM, Materials Performance and Characterization, DOI: 10.1520/MPC20130054
Benefits of using "Simplified" models

- Few fitting parameters needed
  - Many of them are acquired from standard creep and tensile tests
- For the $\Phi$ model no forced "anchoring" to LCF ($N_{f0}$), based on creep, fitted to CF
- For $MH_{CF}$ there is the anchoring to LCF ($N_{f0}$), based on LCF, creep is a correction
- The interpolation and extrapolation with the simplified models have shown robustness and applicability over the whole range of available data

- SIMPLE

- ROBUST
The interaction diagram – time fraction approach  
(RCC-MRx and ASME III-NH)

- Unity for creep fraction \( D_c = \Sigma t/t_r \) is the time to rupture at specified stress and temperature.
- Unity for fatigue fraction \( D_f = \Sigma d_c \) is cycles to failure (LCF) at defined temperature and strain range.
- For design the allowable combined creep and fatigue damage for P91 steel is (0.3, 0.3) interaction locus.
- Allowable number of cycles \( (N_f) \) can be defined (for design) or number of cycles can be predicted (in test result evaluation) with following equations:

\[
N_{CF} = \frac{F}{(1 - C)d_f + Fd_c} \quad \text{if} \quad \frac{d_f}{d_c} < \frac{F}{C}
\]

\[
N_{CF} = \frac{C}{(1 - F)d_c + Cd_f} \quad \text{if} \quad \frac{d_f}{d_c} \geq \frac{F}{C}
\]

where \( d_c \) is the creep component of a single cycle (in most cases represented by the \( N_f/2 \) cycle creep response) and \( d_f \) is the fatigue component of a single cycle (\( 1/N_{f0} \)).
Initial (simple) softening model

- **LCF softening curves** as a function of normalized peak stress ($\sigma_{pN}/\sigma_{p0}$) and cycles to failure ($N_f$ at 25% of drop in stress) are assessed:
  - $\sigma_{p0}$ is the tensile peak stress (virgin material) in the first cycle
  - $\sigma_{pN}$ is the tensile peak stress at cycle $N$

The normalized cyclic peak stress curves fall "nearly" on top of each other ...
First modelling assumption ... they do ...
Softening model

Where $A_1 - A_3$ are $f(R, t_h)$, here $R=-1, t_h=0$ for initial model

Normalized $N/N_f$ with $N_f$ determined from Manson-Coffin model
Predicted peak stress at cycle $N_{1-N_{75\%f}}$

Using modelled value for $\sigma_{p0}$ and Manson-Coffin predicted $N_f$

- 2.5·standard deviations, error $\sim$8% in stress
Example: $600^\circ\ C/\Delta \varepsilon = 1.2\%/t_h = 1080s$

$N_f = 1215$, peak stress decreases, relaxed stress decreases, different rate of decrease ...
Example: 600° C/\Delta\varepsilon=1.2\%/t_h=1080s

\[ N_1 \text{ to } N/N_f = 0.025 \]
\[ 0.025 \leq N/N_f \leq 0.25 \]
\[ 0.25 \leq N/N_f \geq 0.85 \]

increasing relaxation ratio
~ constant relaxation ratio
decreasing relaxation ratio

Average = 0.59, coincides with \( N/N_{f/2} \)
Example CF relaxation curves

Cycle 0 – virgin
Cycle 3 (N/Nf=0.25%)
Cycle 30 (N/Nf=2.5%)
Cycle 240 (N/Nf=20%)
Cycle 610 (N_{f/2})
Cycle 1030 (N/Nf=85%)

As a function of N: relaxed creep strain
Creep damage \( d_c \)
Relaxed strain / sample cycle

Relaxed stress $\Rightarrow$ strain

Virgin material relaxed strain > half life relaxed strain
Predicting cycles to failure $N_f$ using the relaxation of cycle $N$ (for $d_c$)

The first cycle $d_c >>$ half life $d_c$ (life fraction)
Pending work for CF / relaxation / softening

The initial (engineering) softening model for peak stress seems to work well in the strain range 0.5-1.2% at 550 and 600° C.

Extended to incorporate effect of hold times

\[
\frac{\sigma_{p_{N-CF}}}{\sigma_{p_0}} = f\left(\frac{\sigma_{p_{N}}}{\sigma_{p_0}}, t_h\right)
\]

The relaxation model to be chosen for describing \(\sigma(t)\)

ECCC round-robin results as base

- Kohlrausch
- TTP models
- WE-R
- Feltham
- Norton
- Garofalo
MaTISSE test for softening / relaxation modelling

Relaxation and CF (monotonic, cyclic)
- Standard LCF and CF tests with hold times up to 3 h
- Relaxations in different locations of the softening curve
- Relaxations every cycle in the beginning of the curve
Conclusions

Creep and NEC

- New $T_{\text{NEC}}$ curve suggested for RCC-MRx (proposed for P91)
- **New methodology for EN-13445:9 for a number of other steels**

Creep-Fatigue

- New (/old 😊) models for CF life determination (standards)
- Engineering model for softening and relaxation (⇒interaction diagram)
- Verification in MATISSE ...