Creep Performance and Ductility of Martensitic Steels (P91/P92)

Andreas Klenk
Materials Testing Institute University of Stuttgart (MPA)

Michael Schwienheer
Institut für Werkstoffkunde (IfW) Darmstadt
Introduction

Sufficiently high ductility of a material used in pressurized components is an inherent safety margin.

Martensitic steels show beside a higher creep strength mostly a high deformation capability. However, during longterm operation ageing effects in ferritic martensitic materials or precipitations in Nickel based alloys and austenitic materials can provoke a significant reduction of ductility.

Recently a reduction of creep strength was observed when more longterm creep tests have been evaluated. This also provoke discussions about the deformation capability of 9Cr CSEF.

To provide information in this discussion data are sampled from P91 and P92 datasets and the use of parameters describing deformation capability is discussed.
ECCC Dataset: Temperature dependence removing temperature > 650°C

- significant reduction of devaluation by assessing only data up to 650°C
- data at T >= 650°C represent a different material condition and should not be used for a single time-temperature-parameter assessment of all data
Basic information from metallurgical experience

With decreasing stress and longer exposure times a reduction in creep ductility can be observed. Reasons:

- The deformation of the matrix by dislocation glide is smaller for smaller stresses.
- The deformation concentrates on grain boundaries.
- Practically no necking is observed.
Typical Assessment Problems: change of material condition

- tempering temperature: 690°C
  - 650°C: close to change in material properties
  - overestimation of mean curve

Graph showing stress versus temperature for 10% Cr-steel (COST F) with different tempering temperatures.
Dataset P91

ECCC Dataset P91 (2018) with 2817 data points from creep rupture tests at 50 temperatures in the range of 427 to 788°C
Dataset P91

Rupture elongation values of P91 (ECCC dataset 2018), 3 heats indicated with low rupture elongation values.
Dataset P91

Cutting of lower range of rupture elongation values of P91 (ECCC dataset 2018)
ECCC Dataset P92 (2018) with 1030 datasets from creep rupture tests at 22 temperatures in the range of 550 to 760°C
Dataset P92

Rupture elongation values of P92 (ECCC dataset 2018) with indicated temperatures
Dataset P92

Cutting of lower range of rupture elongation values of P92 (ECCC dataset 2018) with indicated product form
Creep Ductility evaluation P91

K.H. Mayer et al.: Creep ductility of new 9-11 Cr steels
NIMS-MPA-IIW-Workshop March 2010, Tsukuba

ECC DATA SHEET Melts

probable flaws in fracture zone

Creep Rupture Elongation at 600°C / 35 000h

0.2- Limit at RT in MPa
Creep Ductility evaluation P92

Creep Rupture Ductility of P92 at 600°C/35,000h versus 0.2-Limit

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E.H. Mayer et al.: Creep ductility of new 9-11 Cr steels
NIMS-MPA-IW-Workshop March 2010, Tsukuba
Strain Exhaustion and influence of non-metallic inclusions, pores, hot-forming defects

Ductility Evaluation of Creep Specimens (DECS)

FE-Assessment of welds
Creep law and modelling
modified Graham-Walles creep law
✓ primary and secondary creep stage
✓ tertiary stage using damage variable D
✓ influence of multiaxial stress states: $q$

\[
\frac{d\varepsilon}{dt} = 10^{A_{11}} \cdot \left[\frac{\sigma}{1 - D}\right]^{n_{11}} \cdot \varepsilon^{m_{1}} + 10^{A_{22}} \cdot \left[\frac{\sigma}{1 - D}\right]^{n_{22}} \cdot \varepsilon^{m_{2}}
\]

\[
\frac{dD}{dt} = 10^{A_{D1}} \cdot \left[\frac{(\sqrt{3}/q)^{\alpha}}{\sigma}\right]^{n_{D1}} \cdot \varepsilon^{m_{D1}} + 10^{A_{D2}} \cdot \left[\frac{(\sqrt{3}/q)^{\alpha}}{\sigma}\right]^{n_{D2}} \cdot \varepsilon^{m_{D2}}
\]

\[
q = \frac{1}{\sqrt{3} \cdot \frac{\sigma_{\text{Mises}}}{\sigma_{\text{Hydro}}}}
\]
Parameters characterising ductility

PLM values and minimum creep rate from parameter approximation procedure for the incremental creep law.
Evaluation and use of numerical results

Application of the procedure to P91
Evaluation of results from numerical calculations

Creep strain $\varepsilon_{III}$ at beginning of tertiary creep stage as a function of rupture time $t_u$

<table>
<thead>
<tr>
<th>Material</th>
<th>uniform rupture strength [%]</th>
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<th>uniform rupture strength [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T/P24</td>
<td>2.00*)</td>
<td>VM12</td>
<td>1.50*)</td>
</tr>
<tr>
<td>T/P91</td>
<td>2.55</td>
<td>X20</td>
<td>1.80</td>
</tr>
<tr>
<td>T/P92</td>
<td>2.14</td>
<td>(*) small amount of data</td>
<td></td>
</tr>
</tbody>
</table>
Creep curves for low stresses

![Diagram showing creep curves for low stresses. The x-axis represents rupture time in hours, and the y-axis represents creep strain. The diagram includes different stress levels, indicated by various symbols and colors. The graph illustrates the behavior of materials under sustained stress, showing how strain increases over time at different stress levels.](image-url)
Influence of heat treatment

Notched hollow cylinders under creep loading
Damage correlation

Probenform: glatte Hohlzylinder
Werkstoff X11CrMoWVNb9-1-1
Belastung: $p_i = 240$ bar, $F_{ax} = 11775$ N
Temperatur: $600$ °C

Zwischenausbau zum Gefügeabdruck 6643 h

Axialdehnung [%] vs. Zeit [h]

- Hohlzylinder, glatt
- X11CrMoWVNb9-1-1

- X11CrMoWVNb9-1-1 (EH2)
- X11CrMoWVNb9-1-1 (EH4)

확실히ş에 대한 조사
Fracture mechanics data - JR curve

- 23°C, as received
- 23°C, aged
- 600°C, as received
- 600°C, aged
- 625°C, as received
- 625°C, aged

J-Integral in N/mm vs. Δa in mm
Creep crack initiation and growth

Fracture mechanics data

- Cs20-specimen
  - $F_{\text{max}} = 4.41 \text{kN}$
  - $K_{\text{IC}} = 13.9 \text{ MPam}^{0.5}$
  - $a_0/W = 0.22$
  - $\Delta a = 0.5 \text{ mm}$

- mean curve P91 for Cs25-specimens, $T=600^\circ\text{C}$
- mean curve 10CrMoWVNbN for Cs25-specimens, $T=600^\circ\text{C}$
- Cs20-specimen P92, $T=625^\circ\text{C}$
Strain-based damage approach

Definition of uniform rupture strain $\varepsilon_{ur}$

High rupture elongation values $A_u$ of uniaxial creep specimen are due to necking → not representative for components

Use of uniform rupture strain $\varepsilon_{ur}$ (determined from creep curves) for the assessment of multiaxial stress states
Strain-based damage approach

Continuous description

Continuous description of $\varepsilon_{ur}$ as a function of time to rupture or stress
S-shape fit in log-log-diagram giving an upper and a lower limit
with regard to conservatism (high stresses) and results from [Klenk2013]
→ implemented into creep routine

$$\varepsilon_{ur} (t) = A_1 + B_1 \cdot e^{-(t/C_1)}$$

$$\varepsilon_{ur} (\sigma) = \frac{A_2 - B_2}{1 + (\sigma/C_2)^{D_2}} + B_2$$
FE-Assessment of welds
Comparison with experimental results

Predicted fracture locations correlate well with experiments.
Predicted rupture times are within a factor of 2.3, when assuming rupture if 50% of cross sectional area reached criterion.
Using $\varepsilon_{ur}(t)$ or $\varepsilon_{ur}(\sigma)$ gives almost the same results.

$\varepsilon_{cr,1} \geq \varepsilon_{ur}(t)$
$\varepsilon_{cr,v} \geq \varepsilon_{ur}(t)$
$\varepsilon_{cr,1} \geq \varepsilon_{ur}(\sigma_{\text{Mis es}})$
$\varepsilon_{cr,v} \geq \varepsilon_{ur}(\sigma_{\text{Mis es}})$

with element deletion:
$\varepsilon_{cr,1} \geq \varepsilon_{ur}(t)$
$\varepsilon_{cr,v} \geq \varepsilon_{ur}(\sigma_{\text{Mis es}})$

no element deletion:
$\varepsilon_{cr,1} \geq \varepsilon_{ur}(t)$
$\varepsilon_{cr,v} \geq \varepsilon_{ur}(\sigma_{\text{Mis es}})$

Comparison with experimental results.

1: BM
4: HAZ

ECCC mean value P91
- ECCC mean value -20%

welded joint AZ

UB

600 °C

tu [h]

tu, predicted [h]

$\sigma_0 [\text{MPa}]$
FE-Assessment of welds
Application to a girth welded component

Agreement with experiment: rupture time and location (HAZ)
Conclusions

The martensitic materials P91/P92 show generally a high ductility but there are some exemptions needing specific consideration

Elongation at rupture or Reduction of area do not represent strain values in components since the development of tertiary creep is geometry and stress dependent. Uniform creep rupture strain was used.

To ensure the integrity components a sufficiently high ductility is necessary. If sufficient ductility cannot be ensured, integrity assessments using fracture mechanics methods and data are necessary.

Fracture mechanics tests on P91 and P92 show high crack resistance (JR-curves) even in aged state and compared to other ferritic materials higher resistance against creep crack initiation and propagation.

Creep strain based damage model based using creep strain limits derived by means of uniform creep rupture strain could be verified by component tests not only for base material but also for welds.
Thank you for your attention