Qualification Strategies for Components Exposed to High Pressure Gaseous Hydrogen

44th MPA-Seminar

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Materials Testing Institute University of Stuttgart (MPA)
Outline

Motivation

Mechanism of Hydrogen Embrittlement

Qualification Strategies on the Example of SAE J 2579

Conclusion and Outlook
Outline

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Qualification Strategies on the Example of SAE J 2579

Conclusion and Outlook
Motivation

Reduction of CO$_2$ and NO$_x$ Emissions is Mandatory

Future Mobility:
Alternative Fuels with Zero Emissions -> Hydrogen

Electricity Production:
Renewable Energy Carriers -> Storage -> Hydrogen

Generation of Hydrogen with Surplus Electricity (Wind, PV) by Electrolysis Possible

Hydrogen Reacts with Oxygen to Water

Increase of Energy Density: Compression

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Conclusion and Outlook
Mechanismus of Hydrogen Embrittlement

Interactions between Material and Compressed Hydrogen

Steps for Hydrogen Intrusion from Gaseous Phase:
1) Molecular Adsorption,
2) Dissociation,
3) Absorption and
4) Diffusion into Metal

Type:
a) Interstitially Integrated
b) Surface and
c) Close to Surface

TRAPS:
d) Grain Boundaries (deep)
e) Dislocations (low)
f) Voids (low)
Effects of Hydrogen Embrittlement

**X3CrNiMo13-4**

- **Helium**
- **Hydrogen**

**X2NiCr19-11 Var.5 (1.4306) -50°C**

- **AV5p3-He**
- **AV5p4-H2**
Testing Methodology

Pressure: 0.1 – 100 Mpa
Load: -100 - +100 kN
Temperature: -50 - +150 °C
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Conclusion and Outlook
Consideration of Hydrogen Impact on Component

Different Standards available for FCEV:

- KHKS 0128
- 2007/46/EG
- CSA CHMC-1
- SAE J 2579

Different standards provide different strategies in order to consider effect of hydrogen on component behavior

Design methods which calculate component lifetime in hydrogen are not available

Workaround: Additional safety factors or special material selection in order to transfer design methods from air to hydrogen

Investigation of impact of different strategies on

- Component cost and
- Component weight
Reference Component

Notched Cylinder
Material: 1.4401

Outer Ø: 10 mm
Notched Ø: 6 mm
Notch Factor: 3.42
# Material Properties

## Chemical Composition

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>[%]</td>
<td>[%]</td>
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<td>[%]</td>
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<td>[%]</td>
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</tr>
<tr>
<td><strong>Certificate</strong></td>
<td>0,015</td>
<td>1,31</td>
<td>0,56</td>
<td>0,023</td>
<td>0,015</td>
<td>16,87</td>
<td>10,04</td>
<td>2</td>
<td>0,044</td>
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<tr>
<td><strong>DEW</strong></td>
<td>≤0,07</td>
<td>≤2,00</td>
<td>≤1,00</td>
<td>Max. 0.045</td>
<td>≤0,030</td>
<td>16,5 to 18,5</td>
<td>10,0 to 13,0</td>
<td>2.00 to 2.50</td>
<td>≤0,10</td>
</tr>
</tbody>
</table>

## Kennwerte

<table>
<thead>
<tr>
<th></th>
<th>$R_{p0.2}$</th>
<th>$R_m$</th>
<th>Fracture Elongation</th>
<th>Reduction of Area</th>
<th>Impact Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>[%]</td>
<td>[N/mm²]</td>
<td>[N/mm²]</td>
<td>[%]</td>
<td>[%]</td>
<td>J</td>
</tr>
<tr>
<td><strong>Certificate</strong></td>
<td>477</td>
<td>522</td>
<td>42</td>
<td>73</td>
<td>237-300</td>
</tr>
<tr>
<td><strong>DEW</strong></td>
<td>Min. 200</td>
<td>500-850</td>
<td>Min. 30</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>DIN EN 10088-3 (2005-09)</strong></td>
<td>Min. 200</td>
<td>500-850</td>
<td>Min. 30</td>
<td>Min. 100</td>
<td></td>
</tr>
</tbody>
</table>
Fatigue Behavior of Component

Intended Lifetime of Component: 10,000 Cycles

Operation Temperature: -50 °C - RT

Lifetime evaluation of notched specimen

**Left: -50 °C**

1.4401 (X5CrNiMo17-12-2)

- \( \sigma_A = 630 \cdot N^{0.108} \quad (s_{\text{guess}} = 0.030) \)
- 10 MPa H2
- \( \sigma_A = 1433 \cdot N^{0.168} \quad (s_{\text{guess}} = 0.010) \)
- 1 MPa He

\( SF = 1.51 \)

**Right: RT**

1.4401 (X5CrNiMo17-12-2)

- \( \sigma_A = 519 \cdot N^{0.095} \quad (s_{\text{guess}} = 0.2001) \)
- 10 MPa H2
- \( \sigma_A = 671 \cdot N^{0.111} \quad (s_{\text{guess}} = 0.2631) \)
- 1 MPa He

\( SF = 1.17 \)
Summary of Reference Component

Allowable Stress Amplitude: 218 MPa *)
Cross Sectional Area $A_{\text{comp}}$: 28,3 mm²
Allowable Load Amplitude: 6,16 kN
Max. Load: 13,7 kN

Component can endure a given
- cyclic load of 13,7 kN
- 10.000 cycles

Component Weight: 37,2 g
Material Costs: 14,2 Ct

*) No safety factor included - survival probability will not impact the result of the following comparison
Qualification Strategy SAE J 2579:

2 Possibilities:
- Reduction of Allowable Stress
- Restriction of Chemical Composition

Aim: No Influence of Hydrogen on Component Behavior
2 Possibilities acc. to Sec. B.2:

- Max. allowable stress: Fatigue Limit
- Increase of Ni-Content $\geq 13\%$

**SAE J 2579, 2018, Table B2 (Excerpt) [SAE 2018]**

<table>
<thead>
<tr>
<th>Material</th>
<th>NWP</th>
<th>Material Composition and Processing</th>
<th>Design Guidance at 1.5xNWP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steel: a,b</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DIN 1.4401 (Germany)</td>
<td>≤ 70 MPa</td>
<td>No restrictions except note b</td>
<td>No significant degradation under hydrogen service for infinite life design$^d$</td>
</tr>
<tr>
<td><strong>Steel: a,b</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DIN 1.4401 (Germany)</td>
<td>≤ 70 MPa</td>
<td>≥13% Ni$^c$ ≤0.25% N$^c$ Note b</td>
<td>No significant degradation under hydrogen service</td>
</tr>
</tbody>
</table>

**Qualification Strategy:** No Hydrogen Influence due to
- Limitation of Stress or
- Modification of Chemical Composition
Determination of max. allowable stress:
Fatigue Strength 1.4401 literature: Lowest boundary of Scatter Band

→ Use of Material Specific Data, own data suggests:
\[ \sigma_{an,\text{max}} = 120 \text{ MPa}, \]
\[ F_a = 6,16 \text{ kN} \]
\[ A_{\text{lim}} = 51,3 \text{ mm}^2 \]

\[
\frac{A_{\text{lim}} - A_{\text{comp}}}{A_{\text{comp}}} = \frac{51,3 - 28,3}{28,3} = 81,3 \%
\]

\[ \Delta A = 81,3 \%
\]

Application of Stress Limitation results in an increase of 81,3 %
- Higher weight
- Higher material costs
Increase in Nickel-Content enhances Hydrogen Compatibility

**Graph:**

- **X2CrNi19-11**

- **Relative Reduction of Area $Z_{H2}/Z_{He}$**

- **Nickel Content [%]**

- **Data Points:**
  - **RT**
  - **- 50 °C**

**Interpretation:**

The graph illustrates the relationship between Nickel Content and the relative reduction of area for X2CrNi19-11. An increase in Nickel Content enhances the hydrogen compatibility, as indicated by the curve's trend towards higher relative reduction of area as Nickel Content increases.
Increase in Nickel Content (10.01% -> 13%):

Assumption: No Influence on Fatigue Strength of Material

Prices of Alloying Elements [IKB2018]:

<table>
<thead>
<tr>
<th>Element</th>
<th>Price / ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>565 $</td>
</tr>
<tr>
<td>Nickel</td>
<td>13.800 $</td>
</tr>
<tr>
<td>Chromium</td>
<td>8.200 $</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>29.800 $</td>
</tr>
</tbody>
</table>
SAE J 2579 (2018) – Chemical Composition

<table>
<thead>
<tr>
<th>Reference Component</th>
<th>Alloying Elements</th>
<th>Price / part (37,2 g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>0,707</td>
<td>14,2 Ct</td>
</tr>
<tr>
<td>Nickel</td>
<td>0,104</td>
<td></td>
</tr>
<tr>
<td>Chromium</td>
<td>0,169</td>
<td></td>
</tr>
<tr>
<td>Molybdenenum</td>
<td>0,020</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component with modified Chemical Composition</th>
<th>Alloying Elements</th>
<th>Price / part (37,2 g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>0,681</td>
<td>15,5 Ct</td>
</tr>
<tr>
<td>Nickel</td>
<td>0,130</td>
<td></td>
</tr>
<tr>
<td>Chromium</td>
<td>0,169</td>
<td></td>
</tr>
<tr>
<td>Molybdenenum</td>
<td>0,020</td>
<td></td>
</tr>
</tbody>
</table>

Application of Modified Chemical Composition results in an increase of 9.0 %
- Higher Material Costs
Overview of Component Costs and Weight

Comparison of resulting components with reference component:

<table>
<thead>
<tr>
<th></th>
<th>Reference Component</th>
<th>Stress Limitation</th>
<th>Restriction of chemical composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight [%]</td>
<td>100</td>
<td>181,3</td>
<td>100</td>
</tr>
<tr>
<td>Weight [abs.]</td>
<td>37,2 g</td>
<td>67,4 g</td>
<td>37,2 g</td>
</tr>
<tr>
<td>Cost [%]</td>
<td>100</td>
<td>181,3</td>
<td>109</td>
</tr>
<tr>
<td>Cost [abs.]</td>
<td>14,2 Ct</td>
<td>25,7 Ct</td>
<td>15,5 Ct</td>
</tr>
</tbody>
</table>
Outlook

Lack of Knowledge in Quantitative Assessment of Hydrogen Effects leads to:
- Large Safety Margings in Design
- Higher Material Costs
- Increased Component Weight

Necessary:
- Better Knowledge of Hydrogen Damage Mechanisms
- Design Methods for Hydrogen Environment

→ Use of Full Material Capabilities
→ Cost and Weight Efficient Components

Path Towards
→ SAFE and AFFORDABLE Mobility of the Future
Literature


[IKB2018] IKB Information Rohstoffpreis-Information, März 2018
Thank You

Dipl.-Ing. Stefan Zickler
Materialprüfungsanstalt Universität Stuttgart
Abteilung Betriebsverhalten unter Medieneinfluss