Behavior of materials used in design of highly stressed engineering components at different temperatures
Considerations contained in the lecture:

1. **Mechanical responses** of materials in service life: stresses, strains, modulus of elasticity, fracture impact energy, creep, fatigue strength (fatigue limit).

2. **Temperature dependence** of mechanical properties

3. **Considered (tested) materials**: 50CrMo4 (1.7228 / AISI 4150); 42CrMo4 (1.7225, AISI 4140); 30CrNiMo8 (1.6580 / AISI 4340); 18CrNi8 (1.5920); 20MnCr5 (1.7147, AISI 5120); 51CrV4 (1.8159 / AISI 6150).

4. **Highly dynamically stressed components** (gears, crankshaft, etc)

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**MATERIAL**

- **$\sigma_{\text{m}}$** - Ultimate tensile strength
- **$\sigma_{0.2}$** - Yield strength
- **$E$** - Modulus of elasticity
- **$K_{\text{IC}}$** - Fracture toughness
- **$\sigma_f$** - Fatigue limit
Particular material is used in defined environmental conditions. This means that material has to be chosen in accordance with the purpose of the structure, with the working / operating conditions, with the choice of the process by which it is to be shaped or joined. Under structure, it is understood any type of construction or machine. Namely, every machine is a construction but every construction is not a machine. In the considered case, such as highly stressed conditions, used material must be able to take high stresses, dynamic loads, and must be creep resistant. Based on such requirements, it is suggested, that material can be exposed to high stresses, high temperatures, creep and fatigue. Regarding the quality and reliability of the structure, taking into consideration the entire structure life from design through manufacture and exploitation, several key problems must be analysed. These problems are: purpose for which structure is intended to be used, working / operating conditions, choice of material, lifetime prediction, safety, common causes of failures, possible (common) failure modes, analyses of how and why structural component has failed, etc. Causes of the failures and appropriate failure modes are interconnected. In engineering practice, structure is usually designed and manufactured in order to guarantee that it does not contain any failure, although this does not have to be the correct enough. As common causes of failures can be mentioned: inadequate choose of material, design errors (used material, the size and shape of an engineering component, properties), manufacturing defects, structural loading, temperature effects, misuse (the structure is subjected to conditions for which it was not designed), assembly errors, improper maintenance, unforeseen operating conditions, inadequate control, etc. These causes, generally, may be divided into pre-existing causes and that appearing in service life. The same applies to failure modes. Commonly observed failures mode in engineering practice are: yielding, creep, fatigue, wear, corrosion, impact, buckling, etc. Any of particular mechanical failure has its cause of origin and the form of expression (mode of representation), i.e., failure mode. In this sense the cause can provide the answer why an engineering component has failed while the failure mode enables the answer how an engineering component has failed. In accordance with the considered problems in this topic, i.e., design of highly stressed engineering components, the following subjects related to the applied materials were explored and analysed: mechanical properties, creep and fatigue of material. Designer who deals with material selection must be familiar with all of mentioned subjects. Some details of investigated responses of considered materials can be found in the literature. Several materials were selected for testing with respect to their use in high-stressed engineering elements, as mentioned above.
# Investigated materials

<table>
<thead>
<tr>
<th>Material / round bar (mm)</th>
<th>Chemical composition (some elements only) mass (%)</th>
<th>As - received</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Cr</td>
</tr>
<tr>
<td><strong>30CrNiMo8 (1.6580 / AISI 4340) / 20</strong></td>
<td>0.29</td>
<td>2.07</td>
</tr>
<tr>
<td><strong>20MnCr5 (1.7147 / AISI 5120) / 18</strong></td>
<td>0.22</td>
<td>1.11</td>
</tr>
<tr>
<td><strong>51CrV4 (1.8159 / AISI 6150) / 20</strong></td>
<td>0.45</td>
<td>1.09</td>
</tr>
<tr>
<td><strong>42CrMo4 (1.7225 / AISI 4140) / 16</strong></td>
<td>0.42</td>
<td>1.07</td>
</tr>
<tr>
<td><strong>50CrMo4 (1.7228 / AISI 4150) / 20</strong></td>
<td>0.487</td>
<td>0.999</td>
</tr>
<tr>
<td><strong>18CrNi8 (1.5920) / 20</strong></td>
<td>0.19</td>
<td>1.8</td>
</tr>
</tbody>
</table>

## Consideration in relation to:

### Material behavior requirements

- **Mechanical properties (σ_m, σ_U, E)**: Higher level for any purpose
- **Creep**: Greater resistance to creep
- **Fatigue**: greater resistance to fatigue - greater fatigue limit
Experiments - used equipment and specimens

Basic testing machine
- Furnace
- High temp. extensometer
- Specimen
- Grip

Dynamic testing machine
- Specimen
- Grip

Charpy impact machine
- Specimen
- Impact pendulum
Mechanical responses - mechanical properties

\[ \sigma - \varepsilon \]

30CrNiMo8
Comparison of some materials
# Temperature dependence of mechanical properties

<table>
<thead>
<tr>
<th>Mat</th>
<th>Temperature (°C)</th>
<th>$\sigma_m$ MPa</th>
<th>$\sigma_{0.2}$ MPa</th>
<th>$E$ GPa</th>
<th>$\sigma_m$ MPa</th>
<th>$\sigma_{0.2}$ MPa</th>
<th>$E$ GPa</th>
<th>$\sigma_m$ MPa</th>
<th>$\sigma_{0.2}$ MPa</th>
<th>$E$ GPa</th>
<th>$\sigma_m$ MPa</th>
<th>$\sigma_{0.2}$ MPa</th>
<th>$E$ GPa</th>
<th>$\sigma_m$ MPa</th>
<th>$\sigma_{0.2}$ MPa</th>
<th>$E$ GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6580</td>
<td>20</td>
<td>696</td>
<td>383</td>
<td>217</td>
<td>634</td>
<td>355</td>
<td>199</td>
<td>616</td>
<td>350</td>
<td>190</td>
<td>702</td>
<td>365</td>
<td>184</td>
<td>534</td>
<td>307</td>
<td>160</td>
</tr>
<tr>
<td>1.7147</td>
<td>100</td>
<td>561</td>
<td>397</td>
<td>219</td>
<td>513</td>
<td>373</td>
<td>206</td>
<td>482</td>
<td>349</td>
<td>192</td>
<td>499</td>
<td>362</td>
<td>184</td>
<td>392</td>
<td>315</td>
<td>177</td>
</tr>
<tr>
<td>1.8159</td>
<td>200</td>
<td>770</td>
<td>642</td>
<td>198</td>
<td>730</td>
<td>592</td>
<td>192</td>
<td>714</td>
<td>608</td>
<td>182</td>
<td>727</td>
<td>613</td>
<td>172</td>
<td>530</td>
<td>481</td>
<td>165</td>
</tr>
<tr>
<td>1.7228</td>
<td>400</td>
<td>1147</td>
<td>1090</td>
<td>1095</td>
<td>1005</td>
<td>1102</td>
<td>912</td>
<td>1014</td>
<td>850</td>
<td>799</td>
<td>694</td>
<td>495</td>
<td>437</td>
<td>-</td>
<td>165</td>
<td>114</td>
</tr>
<tr>
<td>1.5920</td>
<td>500</td>
<td>613</td>
<td>458</td>
<td>215</td>
<td>552</td>
<td>412</td>
<td>207</td>
<td>527</td>
<td>392</td>
<td>197</td>
<td>540</td>
<td>410</td>
<td>181</td>
<td>447</td>
<td>349</td>
<td>176</td>
</tr>
</tbody>
</table>
Creep behavior - comparison

400°C

30CrNiMo8
\[ T = 400°C \text{ = const.} \]
\[ \sigma = 214 \text{ MPa (0.7}\sigma_{0.2}) \]
\[ \sigma = 153 \text{ MPa (0.5}\sigma_{0.2}) \]
\[ \sigma = 91.8 \text{ MPa (0.3}\sigma_{0.2}) \]

20MnCr5
\[ T = 400°C \text{ = const.} \]
\[ \sigma = 221 \text{ MPa (0.7}\sigma_{0.2}) \]
\[ \sigma = 172.6 \text{ MPa (0.546}\sigma_{0.2}) \]
\[ \sigma = 158 \text{ MPa (0.5}\sigma_{0.2}) \]

51CrV4
\[ T = 400°C \text{ = const.} \]
\[ \sigma = 336.7 \text{ MPa (0.7}\sigma_{0.2}) \]
\[ \sigma = 240.5 \text{ MPa (0.5}\sigma_{0.2}) \]
\[ \sigma = 144.3 \text{ MPa (0.3}\sigma_{0.2}) \]

42CrMo4
\[ T = 480°C \text{ = const.} \]
\[ \sigma = 186.5 \text{ MPa (0.5}\sigma_{0.2}) \]
\[ \sigma = 150.4 \text{ MPa (0.4}\sigma_{0.2}) \]
\[ \sigma = 112.8 \text{ MPa (0.3}\sigma_{0.2}) \]

50CrMo4
\[ T = 400°C \text{ = const.} \]
\[ \sigma = 347 \text{ MPa (50}\% \sigma_{0.2}) \]
\[ \sigma = 278 \text{ MPa (40}\% \sigma_{0.2}) \]
\[ \sigma = 208 \text{ MPa (30}\% \sigma_{0.2}) \]

18CrNi8
\[ T = 400°C \text{ = const.} \]
\[ \sigma = 244.3 \text{ MPa (0.7}\sigma_{0.2}) \]
\[ \sigma = 176.5 \text{ MPa (0.5}\sigma_{0.2}) \]
\[ \sigma = 104.8 \text{ MPa (0.3}\sigma_{0.2}) \]
500°C

30CrNiMo8
$T = 500°C = \text{const.}$

$\sigma = 113.5 \text{ MPa} (0.5\sigma_{0.2})$

$\sigma = 68.1 \text{ MPa} (0.3\sigma_{0.2})$

$\sigma = 45.4 \text{ MPa} (0.2\sigma_{0.2})$

50CrMo4

20MnCr5
$T = 500°C = \text{const.}$

$\sigma = 71.7 \text{ MPa} (0.283 \sigma_{0.2})$

$\sigma = 38 \text{ MPa} (0.15 \sigma_{0.2})$

51CrV4

$\sigma = 145.5 \text{ MPa} (0.5\sigma_{0.2})$

$\sigma = 87.3 \text{ MPa} (0.3\sigma_{0.2})$

$\sigma = 58.2 \text{ MPa} (0.2\sigma_{0.2})$

42CrMo4
$T = 580°C = \text{const.}$

$\sigma = 41.7 \text{ MPa} (0.3\sigma_{0.2})$

$\sigma = 27.8 \text{ MPa} (0.2\sigma_{0.2})$

18CrNi8
$T = 500°C = \text{const.}$

$\sigma = 176 \text{ MPa} (0.63\sigma_{0.2})$

$\sigma = 138 \text{ MPa} (0.5\sigma_{0.2})$

$\sigma = 82.8 \text{ MPa} (0.3\sigma_{0.2})$
Calculated fracture toughness-based on tested impact energy (room temp)

<table>
<thead>
<tr>
<th>Material</th>
<th>Charpy impact energy $CVN (J)$ $(V - notch), V = 2\text{mm}$</th>
<th>Calculated fracture toughness $K_{IC} = 8.47(CVN)^{0.63}$ (Roberts-Newton) $K_{IC} (\text{MPa}\sqrt{\text{m}})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30CrNiMo8</td>
<td>79</td>
<td>132.8</td>
</tr>
<tr>
<td>20MnCr5</td>
<td>178</td>
<td>221.6</td>
</tr>
<tr>
<td>51CrV4</td>
<td>24.5</td>
<td>63.5</td>
</tr>
<tr>
<td>42CrMo4 (but only soft annealed)</td>
<td>166</td>
<td>212</td>
</tr>
<tr>
<td>50CrMo4</td>
<td>69</td>
<td>122</td>
</tr>
<tr>
<td>18CrNi8</td>
<td>220</td>
<td>253</td>
</tr>
</tbody>
</table>
Fatigue testing, fatigue strength, fatigue limit

30CrNiMo8

![Graph for 30CrNiMo8 showing the relationship between maximum stress (σ_max) and number of cycles to failure (N) with the equation \( \sigma = -27.584 \log N + 466.942 \) and fatigue limit \( \sigma_f = 280.4 \text{ MPa} \).]

51CrV4

![Graph for 51CrV4 showing the relationship between maximum stress (σ_max) and number of cycles to failure (N) with the equation \( \sigma = -54.063 \log N + 585.153 \) and fatigue limit \( \sigma_f = 251.08 \text{ MPa} \).]
Fatigue testing, fatigue strength, fatigue limit

**42CrMo4**

\[
\sigma_{\text{max}} = -86.1565 \log N + 1126.603
\]

\(R = 0.25\)

\(\sigma_f = 52.26 \text{ MPa}\)

**18CrNi8**

\[
\sigma_{\text{max}} = -27.455 \log N + 477.285
\]

\(R = -1\)

\(\sigma_f = 285.1 \text{ MPa}\)
Fatigue limit calculation-modified staircase method

**Case: 30CrNiMo8**

Table: Data related to failed (♦) and non-failed (∘) specimens used in modified staircase method

<table>
<thead>
<tr>
<th>Stress $\sigma_i$/MPa</th>
<th>Specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td>290</td>
<td>♦</td>
</tr>
<tr>
<td>285</td>
<td>♦</td>
</tr>
<tr>
<td>280</td>
<td>♦</td>
</tr>
</tbody>
</table>

Table: Data analysis for modified staircase method ($f$ – failed)

<table>
<thead>
<tr>
<th>Stress $\sigma_i$/MPa</th>
<th>Stress level, i</th>
<th>$f_i$</th>
<th>$i_f$</th>
<th>$i^2_f_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>290</td>
<td>2</td>
<td>3</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>285</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>280</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\sum f_i.i_f.i^2f_i$</td>
<td>5</td>
<td>8</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>

Table: Constants ($A$, $B$, $C$ and $D$) according to ISO 12107

<table>
<thead>
<tr>
<th>Stress ratio $R = -1$, room temperature</th>
<th>$A$</th>
<th>$B$</th>
<th>$C$</th>
<th>$D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formula $30$CrNiMo8</td>
<td>8</td>
<td>14</td>
<td>5</td>
<td>0.24</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\sigma_f(P,1-\alpha) &= \bar{\mu}_y - k_{(P,1-\alpha)} \cdot \bar{\sigma}_y, \\
\mu_y &= \sigma_0 + d \left( \frac{A}{C} - \frac{1}{2} \right) \ldots \text{the mean fatigue strength} \\
\bar{\sigma}_y &= 1.62 \cdot d (D + 0.029) \ldots \text{estimated standard deviation of fatigue strength} \\
k_{(P,1-\alpha,y)} &= k_{(0.1;0.9;6)} = 2.333 \\
\bar{\sigma}_y &= 1.62 \cdot d (D + 0.029) \\
R = -1 \rightarrow \bar{\mu}_y &= \sigma_0 + d \left( \frac{A}{C} - \frac{1}{2} \right) = 280 + 5 \left( \frac{8}{5} - \frac{1}{2} \right) = 285.5 \text{ MPa}
\end{align*}
\]
\[ R = -1 \rightarrow \sigma_y = 1.62 \cdot d(D + 0.029) = 1.62 \cdot 5(0.24+0.029) = 2.179 \text{ MPa} \]

Fatigue limit in accordance with eq. (3), is:
\[ R = -1 \rightarrow \sigma_f(0.1;0.9;0.6) = \bar{\mu}_y - k_{(p,1-\alpha,y)} \cdot \bar{\sigma}_y = 285.5 -2.333 \cdot 2.179 = 280.4 \text{ MPa}. \]
## Conclusions

<table>
<thead>
<tr>
<th>Material</th>
<th>$\sigma_m$ MPa</th>
<th>$\sigma_{0.2}$ MPa</th>
<th>Charpy energy &amp; $K_{ic}$ CVN (J) /$K_{ic}$ (MPa $\sqrt{m}$)</th>
<th>Creep resist. (at approx. 0.3$\sigma_{0.2}$ ~ 70-80MPa)</th>
<th>Fatigue MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T°C</td>
<td>T°C</td>
<td>T°C</td>
<td>T°C/R = −1</td>
<td></td>
</tr>
<tr>
<td>30CrNiMo8</td>
<td>20</td>
<td>500</td>
<td>20</td>
<td>500</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>696</td>
<td>303</td>
<td>383</td>
<td>228</td>
<td>79/132.8</td>
</tr>
<tr>
<td>20MnCr5</td>
<td>561</td>
<td>265</td>
<td>397</td>
<td>253</td>
<td>178/221.6</td>
</tr>
<tr>
<td>51CrV4</td>
<td>770</td>
<td>334</td>
<td>642</td>
<td>291</td>
<td>24.5/63.5</td>
</tr>
<tr>
<td>42CrMo4 (soft annealed)</td>
<td>735</td>
<td>580/1</td>
<td>593</td>
<td>580/1</td>
<td>166/212</td>
</tr>
<tr>
<td>50CrMo4</td>
<td>1147</td>
<td>495</td>
<td>1090</td>
<td>437</td>
<td>69/122</td>
</tr>
<tr>
<td>18CrNi8</td>
<td>613</td>
<td>295</td>
<td>458</td>
<td>276</td>
<td>220/253</td>
</tr>
</tbody>
</table>
Acknowledgment

• This work has been financially supported by the University of Rijeka within the project: uniri-technic-18-42, “Investigation, analysis and modeling the behavior of structural elements stressed at room and high temperatures”
THANK YOU FOR YOUR ATTENTION