Relationships between tensile and fracture mechanics properties and fatigue properties of large plastic mold steel

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Relationships between Tensile and Fracture Mechanics Properties and Fatigue Properties of Large Plastic Mold Steel

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¹Politecnico di Torino  ²Università di Genova  ³Politecnico di Milano  ⁴Lucchini Sidermeccanica
Overall views of a bumper mould.
Summary

• Production cycle and critical issues of large plastic moulds
• Sampling pattern and re-heat-treatments
• As-received microstructures
• Mechanical properties and fatigue behaviour of as-received and re-heat-treated steel
• Fracture surfaces
• Conclusions
Plastic molds machined from 1x1x2 m forged and pre-hardened steel blooms

Applications

- automotive components (bumpers, dashboards, ...)

Stresses

- applied stresses:
  - injection pressure
  - thermal gradients
  - notch effects
  - wear by reinforced resins flow
  - fatigue (millions of pieces)

- stresses raised by:
  - cracks (improper weld bed depositions),
  - abnormal operations (incomplete extraction).

- Experience-based design, no usual defect-allowance calculation procedure
- Reported macroscopically brittle in-service failures

- different microstructures expected at increasing depths after quench
- any microstructure could be found at mold face
### Steel composition

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Cr</th>
<th>Mn</th>
<th>Ni</th>
<th>Mo</th>
<th>Si</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2738</td>
<td>0.35</td>
<td>1.8</td>
<td>1.3</td>
<td>0.9</td>
<td>0.15</td>
<td>0.2</td>
<td>&lt;0.03</td>
<td>&lt;0.03</td>
</tr>
<tr>
<td>40CrMnNiMo8-6-4</td>
<td>0.45</td>
<td>2.1</td>
<td>1.6</td>
<td>1.2</td>
<td>0.25</td>
<td>0.4</td>
<td>&lt;0.03</td>
<td>&lt;0.03</td>
</tr>
<tr>
<td>Examined bloom</td>
<td>0.42</td>
<td>2.0</td>
<td>1.5</td>
<td>1.1</td>
<td>0.21</td>
<td>0.37</td>
<td>0.002</td>
<td>0.006</td>
</tr>
</tbody>
</table>

### Steel mill operations

- ingot casting (ESR refining is not possible)
- forging to 1x1 m sections
- dehydrogenization
- oil quenching
- tempering (one or more stages)
Usual Production cycle (II)

- **Commercial warehouse operations**
  - removal of rough and decarburized surfaces (up to 10-20 mm)
  - sawing to requested dimensions

- **Mold machining shop operations**
  - chip-removal and/or electrical-discharge machining to the mold shape
  - grinding with or without polishing in selected areas
  - local surface treatments
  - eventual corrections using weld bed depositions
Forging

- comparable ingot and bloom section
- some repeated forging steps

- total reduction ratio much lower than in rolling (and not comparable)

Heat treating in air

<table>
<thead>
<tr>
<th>Step</th>
<th>Temperature</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydrogen removal</td>
<td></td>
<td>a few days</td>
</tr>
<tr>
<td>austenitizing</td>
<td>840-880°C</td>
<td>1-2 days</td>
</tr>
<tr>
<td>oil quench</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>tempering to 330-300 HB</td>
<td>550-600°C</td>
<td>1-2 days (each stage)</td>
</tr>
</tbody>
</table>
Experimental (I): sampling of the original bloom

Forged & heat-treated surfaces

Mould blank

Slab

Residual

12x18 mm section blanks

38 mm thick $K_{IC}$ specimens (LT)

As-received

Individually re-heat-treated

[mm]
Experimental (II): sampling pattern & re-heat-treatments

- 38 mm re-heat-treated $K_{IC}$ specs.
- 38 mm as-received $K_{IC}$ specs.
- Round tensile specs. (L)
- Metallographic samples
- Re-heat-treated Charpy-V specs. (LT)
- Charpy-V specs. (LT)
- Rotating bending fatigue specimens (L)

Re-heat-treatments: $860°C \frac{3}{4}h / N_2$ or air / $590°C 3h / 550°C 3h$
As-received microstructures vs. depth (Nital etch)

55 mm depth

105 mm

450 mm

650 mm - core
Hardness, tensile and fracture toughness tests

Hardness [HV100]

<table>
<thead>
<tr>
<th>Depth [mm]</th>
<th>0</th>
<th>200</th>
<th>400</th>
<th>600</th>
<th>800</th>
<th>1000</th>
<th>1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>440 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>145 mm (I)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>145 mm (II)</td>
<td></td>
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<tr>
<td>RHT</td>
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</table>

Tensile properties [MPa]

<table>
<thead>
<tr>
<th>Depth [mm]</th>
<th>0</th>
<th>200</th>
<th>400</th>
<th>600</th>
<th>800</th>
<th>1000</th>
<th>1200</th>
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<tbody>
<tr>
<td>YS</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>UTS</td>
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<tr>
<td>YS, RHT</td>
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</table>

Hardening exponent

<table>
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<th>Depth [mm]</th>
<th>0</th>
<th>200</th>
<th>400</th>
<th>600</th>
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<td>YS, RHT</td>
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</tr>
</tbody>
</table>

KIC [MPa√m]

<table>
<thead>
<tr>
<th>Depth [mm]</th>
<th>0</th>
<th>200</th>
<th>400</th>
<th>600</th>
<th>800</th>
<th>1000</th>
<th>1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-received</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RHT</td>
<td></td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>
Charpy-V tests & transition curves

Transition curves

175 °C tests

As received steel
**Survival Probability**

<table>
<thead>
<tr>
<th>Stress [MPa]</th>
<th>As-received</th>
<th>Re-heat-treated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Core (~560 mm)</td>
<td>Surface (~140 mm)</td>
</tr>
<tr>
<td>10%</td>
<td>518</td>
<td>581</td>
</tr>
<tr>
<td>90%</td>
<td>469</td>
<td>537</td>
</tr>
<tr>
<td>50%</td>
<td>493 19</td>
<td>559 17</td>
</tr>
</tbody>
</table>

Rotating bending fatigue tests – 4.2 Mcycles endurance limit

Staircase method (example below: core as-received specimens)

| test n. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | X | 0 |
|---------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|   |   |
| [MPa]   |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |   |   |
| 500     | X | X |   |   |   | X |   |   |   |    |    |    |    |    |    |   |   |
| 490     | O | X | X |   |   | O | X |   |   |    |    |    |    |    |    |   |   |
| 480     | X | O | X | O | X | X | O |   |   |    |    |    |    |    |    |   |   |
| 470     | O | O | O | O | O | O | O | X | X |    |    |    |    |    |    |   |   |
| 460     | O | O | O | O | O | O | X | O | X |    |    |    |    |    |    |   |   |
| 450     | O | O | O | O | O | O | O | O | O |    |    |    |    |    |    |   |   |

25% increase
Fractography (I): Charpy-V test - brittle areas (as received specs.)

40 mm depth
intergranular

123 mm depth
intergranular & cleavage

667 mm depth
quasi-cleavage & ductile areas
Fractography (II): $K_{lc}$ tests – as received specs.

- 60 mm depth – intergranular & cleavage
- 395 mm depth – cleavage & ductile areas
Fractography (III): $K_{lc}$ tests – re-heat-treated specs.

Fatigue precrack

Brittle propagation
Fractography (IV): fatigue tests – fatigue areas

As-received

Surface (~140 mm)

Core (~560 mm)

Re-heat-treated

50 µm

50 µm
Fractography (V): fatigue tests – overload areas

Surface (~140 mm) intergranular

Core (~560 mm) cleavage & ductile

Re-heat-treated (originally ~560 mm) intergranular (partially ductile)
Fractography (VI): remarks

Macroscopically brittle (overload) fracture mechanisms

• Charpy-V, $K_{lc}$ and fatigue test specimens with similar microstructures show similar microscopic fracture mechanisms.

• Core and intermediate depth as-received microstructures show cleavage or quasi-cleavage fracture with some ductile areas.

• Both as-received (low depth) and re-heat-treated tempered martensite microstructures show mainly intergranular fracture.

Toughness of tempered martensite microstructures

• Only the re-heat-treated samples show ductile regions at the crack tip of the $K_{lc}$ specs. (and thus higher toughness).

• Differences in the tempered martensite carbide distribution, not observable by the O.M., must be supposed.
Conclusions (I)

- Mixed microstructures occur throughout the examined bloom.
- The bloom fracture toughness is exceptionally low (about 40 MPa√m) for a Q&T steel, considering the achieved UTS.
- The plain-strain fracture prevalently occurs by decohesion, coherently with the fact that, at room temperature, this steel is in its brittle temperature range.
- The low toughness must be attributed to the microstructures caused by the heat treatment, and in turn to the large dimensions of the blooms and of the moulds.
- The much higher toughness of the re-heat-treated samples must be attributed to microstructural differences on a sub-micron scale.
Conclusions (II)

- The rotating bending fatigue endurance limits scale with the tensile strength, rather than with the fracture toughness.
- The endurance limits of the re-heat-treated samples is 25% higher, keeping the differences due to the original location.
- The low fracture toughness is a critical property; the lower fatigue endurance limit allows for a critical crack to develop more rapidly than in a fully Q&T condition.
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\textsuperscript{3}Politecnico di Milano  \hspace{1cm}  \textsuperscript{4}Lucchini Sidermeccanica

Thank you for your attention!