Relation between toughness, infinite fatigue life and microstructure in large blooms for automotive plastic molds.

Original

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RELATION BETWEEN TOUGHNESS, INFINITE FATIGUE LIFE AND MICROSTRUCTURE IN LARGE BLOOMS FOR AUTOMOTIVE PLASTIC MOLDS.

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Lucchini Sidermeccanica S.p.A.
Overall views of a bumper mold.
Plastic molds machined from 1x1x3 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
Usual Production cycle

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 40CrMnNiMo8-6-4</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>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)

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>
<tr>
<td>(two stages)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Sampling

Forged & heat-treated surfaces

Mold blank

Residual

Blanks

Hardness & metallography

Round tensile specs.

38 mm thick $K_{IC}$ specimens

Charpy specs.

Depth

480

1190

1285

1642.5

1327.5

1036
Sampling (cont.): fatigue specimens

Rotating bending fatigue specimens (L)

Subsurface
Close-to-core

38 mm $K_{IC}$ specimens
**Metallography – microstructures vs. depth** *(Nital etch)*

- **55 mm depth**
  - Tempered martensite, retained austenite transformed during tempering.

- **450 mm**
  - Fine and ultra-fine pearlite, upper bainite modified by tempering

- **105 mm**
  - Lower bainite modified by tempering, retained austenite transformed during tempering

- **Fine pearlite, upper bainite modified by tempering**
Mechanical properties: hardness, tension, fracture toughness

Charpy KV impact absorbed energy
50% FATT: Core 150°C - Surface 270°C

Hardness decreases from surface to core.

Tensile properties are adequate at the surface and decrease markedly at core (esp. YS).

Fracture toughness values are rather low.
Metallography: microstructures at chosen positions (Nital etch)

Subsurface position (156 mm depth)

Close-to-core position (552 mm depth)
Lower bainite modified by tempering

Retained austenite with finely scattered dark carbides due to its transformation during tempering

Pearlite is completely absent.

Metallography: subsurface microstructure – detail (Nital etch)
Fine and ultra-fine pearlite

Upper bainite, modified and subjected to carbide coarsening during the tempering stages

(lightly attached upper bainite)
Rotating Bending Fatigue

- All samples have been machined from the two halves of two broken $K_{lc}$ samples, one near the surface (B14) and the other next to the core (B9).

$D_{min \ (nom)} = 6 \text{ mm}$

![Diagram of sample dimensions with $W$, $L/2$, and $B$ labels.]
Rotating Bending Fatigue

For each of the two broken $K_{lc}$ samples, two different conditions have been investigated:

- Samples from two halves were tested in the original condition (B9 and B14);
- Samples from the other two halves were tested after air quenching and double tempering (B9T and B14T). Austenitization was carried out at about $860^\circ C$ for 45 minutes, the first tempering at $590^\circ C$ for 3 hours and the second at $550^\circ C$ for 3 hours.
Rotating Bending Fatigue

$\sigma_D$ values were calculated according to the staircase method (UNI-3964); the maximum number of cycles was assumed at $4.2 \cdot 10^6$ (frequency = 50 Hz). Here follows an example.

<table>
<thead>
<tr>
<th>Test n.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$[MPa]</td>
<td>540</td>
<td>530</td>
<td>520</td>
<td>510</td>
<td>500</td>
<td>490</td>
<td>480</td>
<td>470</td>
<td>460</td>
<td>450</td>
<td>440</td>
<td></td>
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<td>O</td>
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<td>O</td>
<td></td>
</tr>
</tbody>
</table>

$o = \text{test passed}$

$x = \text{test failed}$
Rotating Bending Fatigue Limits -Results-

- The material near the surface has a better fatigue behaviour than the one next to core

- Re-heat treatment highly improves the fatigue limit (25%)

<table>
<thead>
<tr>
<th></th>
<th>Depth [mm]</th>
<th>$\sigma_D$ (50%) [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B9</td>
<td>625</td>
<td>493</td>
</tr>
<tr>
<td>B9T</td>
<td>625</td>
<td>618</td>
</tr>
<tr>
<td>B14</td>
<td>181</td>
<td>559</td>
</tr>
<tr>
<td>B14T</td>
<td>181</td>
<td>700</td>
</tr>
</tbody>
</table>
Fractography (As-received specs.)

Fatigue fracture surface

Subsurface

Close-to-core

Overload fracture surface

Subsurface

Close-to-core

Initiation at inclusions was rare
Fractography: fatigue areas

As-received

Re-heat-treated
Fractography: overload areas

As-received

Re-heat-treated

Subsurface

Close-to-core
Conclusions

Mixed microstructures occur throughout a pre-hardened steel bloom for dies apt to large plastic components fabrication.

The fracture toughness is exceptionally low for a Q&T steel. At the tested depths, $K_{IC}$ values were 38 MPa√m ca. close to the bloom surface and 43 MPa√m ca. near the core.

The low toughness is attributed to the slack quench, due to the large molds dimensions (1x1x3 m).

Endurance limits were about 560 MPa for the steel close to the surface and 495 MPa for the steel near the core. They scale with the steel tensile strength, not with its fracture toughness.

Endurance limits for samples individually re-heat-treated increased 25%, keeping the differences due to the location.
This presentation was titled

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The authors were Italian

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THANK YOU FOR YOUR ATTENTION