Increased performance by post weld improvement techniques

Mansoor Khurshid and Zuheir Barsoum
Increased performance by post weld improvement techniques

<table>
<thead>
<tr>
<th>Fatigue strength [MPa]</th>
<th>Yield strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate</td>
<td>HFMI treated</td>
</tr>
<tr>
<td>Plate with hole</td>
<td>weld</td>
</tr>
<tr>
<td>Improved weld quality</td>
<td>As welded</td>
</tr>
</tbody>
</table>

DEPARTMENT OF AERONAUTICAL AND VEHICLE ENGINEERING,
DIVISION OF LIGHTWEIGHT STRUCTURES


- Residual stresses induced in HFMI treated S355, S700MC and S960 steel plates
- Indentation depth are measured for input into simulations
- Plates treated only one time
Residual stress state induced in non welded plates – FE modelling

- Residual stress are measured experimentally and estimated numerically
- Displacement controlled simulations with strain rate dependent combined material model gives better estimation
- Evaluate different modelling techniques, material models
Observation

- **Compressive residual stresses up to a depth of 2 mm** are induced by HFMI treatment in S355, S700MC, S960 steels.
- **The HFMI treatment intensity had no influence on the residual stress state in S355 steel**; however, in S700MC the maximum peak of the induced residual stresses is shifted deeper into the material. This is only observed for the specimens peened only one time.
- **Residual stress state to a depth of less than 0.8 mm can be estimated qualitatively well using simple isotropic or strain rate dependent isotropic hardening models.** However, the accuracy of residual stress state estimated by simulations with combined hardening and strain rate dependent combined models is higher at larger depths. Combined hardening model can be the most appropriate hardening model for simulating residual stress state if residual stress relaxation is studied or fatigue life is estimated by finite element analyses.
Stability of high frequency mechanical impact (HFMI) post-treatment induced residual stress states under cyclic loading of welded steel joints

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- Review of analytical models for cyclic residual stress relaxation
- Numerical simulation loop established which could estimate residual stresses and residual stress relaxation qualitatively good
- Experimental validation by fatigue testing and residual stress relaxation measurements.
Analytical models for cyclic residual stress relaxation

\[
\sigma_{mN} = \sigma_{m1} \cdot N^B
\]

\[
\sigma_{res}^N = A + m \cdot \log(N)
\]

\[
\frac{\sigma_{res}^N}{\sigma_0^{res}} = A \cdot \left( \frac{\sigma_{max} \cdot \sigma_a}{(C_w \cdot C_y)^2} \right)^m \cdot (N - 1)^B - 1
\]

\[
\frac{\sigma_{res}^N}{|\sigma_0^{res}|} = A \cdot \left( \frac{2 \cdot \sigma_a^2}{(1-R) \cdot (C_w \cdot C_y)^2} \right)^m \cdot (N - 1)^B - 1
\]

Models developed for relaxation of residual stress due to shot peening

\[
\frac{(\sigma_{res})_{relax}}{(\sigma_{res})_{1\,cycle}} = N^k
\]

for \(\frac{(\sigma_{res})_{ini} + \sigma_{app}}{\sigma_y} < 1\)

\[
\frac{(\sigma_{res})_{relax}}{(\sigma_{res})_{ini}} = N^{-0.004}
\]

for \(\frac{(\sigma_{res})_{ini} + \sigma_{app}}{\sigma_y} \geq 1\)

\[
\frac{\sigma_{mN}}{\sigma_{m1}} = \frac{\sigma_y - \sigma_a}{\sigma_m1} - \left( \frac{\sigma_a}{\sigma_y} \right)^b \cdot \log(N)
\]

\[
S = \left[a \cdot \left( \frac{\sigma_a}{\sigma_y} \right)^n + b \cdot [\log(N + 1)]^m \right]
\]

\[
\frac{\sigma_{res}^{mN}}{\sigma_0^{res}} = A \cdot \left( \frac{1}{C_w} \right)^m \cdot N^B
\]

\[
C_w = K_1 \cdot H^2 + K_2 \cdot H + K_3
\]
Base material and specimen geometry

Nominal mechanical properties of mild steel S355 base and filler material.

<table>
<thead>
<tr>
<th>Type</th>
<th>Yield strength [MPa]</th>
<th>Ultimate tensile strength [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base material</td>
<td>355</td>
<td>575</td>
<td>22</td>
</tr>
<tr>
<td>Filler material</td>
<td>440</td>
<td>530</td>
<td>30</td>
</tr>
</tbody>
</table>

Comparison of weld toe condition

- As-welded
- HFMI-treated

Application of HFMI-treatment
Residual stress condition before cyclic loading (S355 vs. S960)
Residual stress condition after cyclic loading (S355)

- Cyclic loading with comparably minor nominal stress range (load-level at run-out region of test-results)
- Significant decrease of compressive residual stress state after first load
- Further relaxation up to fifty million load-cycles (run-out specimen)
Structural weld simulation (I)
Structural weld simulation (II) and numerical analysis of HFMI treatment
Results from numerical simulation (S355)

Resulting residual stress results after HFMI-treatment.

<table>
<thead>
<tr>
<th>X-ray measurement</th>
<th>HFMI simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual stress in transversal (loading) direction at surface layer of weld toe [MPa]</td>
<td></td>
</tr>
<tr>
<td>–335</td>
<td>–319</td>
</tr>
</tbody>
</table>

- Indentation depth similar to measurements
- Residual stress measurements agree well to X-ray

Nominal load stress history for simulation of five load-cycles ($\Delta\sigma_n = 250$ MPa and $R = 0.1$).

<table>
<thead>
<tr>
<th>Step number</th>
<th>#1 (N = 1)</th>
<th>#2</th>
<th>#3 to #10 (N = 2 to 5)</th>
<th>#11</th>
<th>#12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local load stress $\sigma$ in transversal (loading) direction at surface of weld toe [MPa]</td>
<td>Load stress</td>
<td>278</td>
<td>27.8</td>
<td>278 and 27.8</td>
<td>153</td>
</tr>
</tbody>
</table>

Residual stress states after cyclic loading at $\Delta\sigma_n = 250$ MPa and $R = 0.1$.

<table>
<thead>
<tr>
<th>N = 0</th>
<th>N = 1</th>
<th>N = 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual stress in transversal (loading) direction at surface of weld toe [MPa]</td>
<td>X-ray Measurement</td>
<td>–335</td>
</tr>
<tr>
<td>Numerical simulation</td>
<td>–319</td>
<td>–201</td>
</tr>
</tbody>
</table>

- Numerical analysis of cyclic loading up to N=5
- Significant relaxation after first load-cycles
- Analytical model suitable after first load-cycle
Behavior of Compressive Residual Stresses in High Strength Steel Welds Induced by High Frequency Mechanical Impact Treatment

Residual stress zone plays an important role in the fatigue life of welded structures. The effect can be beneficial or detrimental, depending on the nature of residual stresses. High frequency mechanical impact (HFMI) treatment is a postweld fatigue improvement technique for welded joints. In this research work the behavior of compressive residual stresses induced in welded joints in high strength steels (HSS) by HFMI treatment has been investigated. Longitudinal residual carrying attachments in HSS are tested with constant amplitude (CA) and variable amplitude (VA) fatigue loading. Stress concentration factors have been calculated using finite element analysis (FEA). Residual stresses have been measured at different cycles during fatigue testing using X-ray diffraction technique. It is observed that the induced residual stresses are quite stable with some relaxation in CA and VA loading. The overload in VA loading seem to be more detrimental. Relaxation of residual stresses is more obvious in VA tests. [DOI: 10.1115/1.4026651]
Residual stress condition after cyclic loading (CAL)

<table>
<thead>
<tr>
<th>Specimen number</th>
<th>Types of test</th>
<th>Frequency</th>
<th>Stress ratio</th>
<th>Stress range CA loading (MPa)</th>
<th>Equivalent stress range VA loading (MPa)</th>
<th>Maximum stress range VA loading (MPa)</th>
<th>Number of cycles until failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CA</td>
<td>12</td>
<td>-1</td>
<td>400</td>
<td>Not applicable</td>
<td>Not applicable</td>
<td>729,700</td>
</tr>
<tr>
<td>2</td>
<td>CA</td>
<td>12</td>
<td>-1</td>
<td>500</td>
<td>Not applicable</td>
<td>Not applicable</td>
<td>256,500</td>
</tr>
<tr>
<td>3</td>
<td>VA</td>
<td>20</td>
<td>-1</td>
<td>Not applicable</td>
<td>514</td>
<td>585</td>
<td>773,736</td>
</tr>
<tr>
<td>4</td>
<td>VA</td>
<td>20</td>
<td>-1</td>
<td>Not applicable</td>
<td>310</td>
<td>585</td>
<td>346,748</td>
</tr>
</tbody>
</table>

![Graph showing residual stresses over distance from weld toe for various cycle counts with Kt values of 2.2 and 2.03.](image)
Residual stress condition after cyclic loading (VAL)

<table>
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<td>CA</td>
<td>12</td>
<td>−1</td>
<td>500</td>
<td>Not applicable</td>
<td>Not applicable</td>
<td>756,500</td>
</tr>
<tr>
<td>3</td>
<td>VA</td>
<td>20</td>
<td>−1</td>
<td>Not applicable</td>
<td>314</td>
<td>585</td>
<td>773,756</td>
</tr>
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<td>4</td>
<td>VA</td>
<td>20</td>
<td>−1</td>
<td>Not applicable</td>
<td>510</td>
<td>585</td>
<td>740,748</td>
</tr>
</tbody>
</table>

K_t = 1.97

![Residual stresses vs. distance from weld toe](image)

![Percentage of applied load vs. number of cycles](image)

![Load vs. number of cycles](image)
Conclusions (I)

• **Compressive residual stresses up to a depth of 2 mm** are induced by HFMI treatment in S355, S700MC,S960 steels.

• **The HFMI treatment intensity had no influence on the residual stress state in S355 steel**; however in S700MC the maximum peak of the induced residual stresses is shifted deeper into the material. This is only observed for the specimens peened only one time.

• **Residual stress state to a depth of less than 0.8mm can be estimated qualitatively well using simple isotropic or strain rate dependent isotropic hardening models.** However, the accuracy of residual stress state estimated by simulations with combined hardening and strain rate dependent combined models is higher at larger depths. Combined hardening model can be the most appropriate hardening model for simulating residual stress state if residual stress relaxation is studied or fatigue life is estimated by finite element analyses.
Conclusions (II)

• The magnitude of induced residual stresses increased with a rise in treatment frequency and pin tip radius

• X-ray measurements for S355 and S960 longitudinal stiffener specimens reveal that due to cyclic loading a significant reduction of the beneficial compressive residual stress state at the HFMI treated end-of-seam weld toe area occurs. This relaxation process takes places in the low- and high-cycle fatigue region at comparably minor stress ranges near the run-out stress level

• The presented numerical simulation chain incorporating both structural welding and HFMI-treatment simulation shows that the final residual stress states after each manufacturing process are in sound agreement to the measurements with a maximum difference of only 5%.

• A consecutive numerical-analytical procedure is presented, which is well suitable in case of the investigated specimen type and mild steel material.
Conclusions (III)

- The stresses induced by HFMI had a **stable behavior** for most of the fatigue life for the applied stress range in **CA** loading tests.

- The **overloads in VA** loading are observed to **cause some relaxation** in the compressive residual stresses; however, the stress relaxation rate is slow and even compressive residual stresses were measured before failure.

- Testing with a **higher stress range** may lead to **prominent relaxation** of the stresses.
Thank you for your kind attention