MEASUREMENT OF RESIDUAL STRESS DISTRIBUTION IN TUBULAR JOINTS CONSIDERING POST WELD HEAT TREATMENT

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ABSTRACT

One of the most important connections in tubular structures is the welded joints called clusters or nodes. These connections are subject to the highest stresses and fatigue loadings and thus are the most probable position of cracking. In this work research has been conducted to determine the benefit of post weld heat treatment (“PWHT”) of connections to improve fatigue life of these clusters.

This paper describes investigations conducted on residual stress measurements using hole-drilling techniques in tubular boom clusters. Residual stress and other material characteristics were measured before and after heat treatment and the results used related to the fatigue performance of the connections with and without PWHT. The results indicate that PWHT could be a major contributor to improved performance.

Keywords: Welding, Clusters, Nodes, Hole Drilling, Residual Stress, Fatigue, Tubular Structures

1. INTRODUCTION

Tubular structures are used for large civil structures such as bridges, offshore structures and materials handling machinery. Perhaps the most demanding of these in regard to integrity, is the boom of large mining draglines, where the structure is swung from side to side under high accelerations and loadings approximately once every minute, resulting in about 500,000 fatigue cycles per year.

In these booms, fatigue cracking commonly occurs at the overlapping connections of the main chords and the lacings. The cost of detecting and repairing cracking in these structures is a significant cost item for the mining industry¹.

The cause of cracking is complex. Normally stress concentrations arise around flaws/defects such as slag inclusions or incomplete fusion in welds and this is often implicated in cracking. For predicting fatigue life of weldments, previous investigations have developed experimental methods to determine the fatigue behavior of weld structures at locations of defects² and at weld toes³.

Residual stresses, which arise in the welded joints as a consequence of strains caused by solidification, phase change and contraction during welding, also affect the fatigue behavior of welds. In particular, tensile residual stress of yield magnitude may exist in as-welded structures and may cause detrimental effects to the fatigue behavior of welded structures.

For estimating total life, the normal approach to fatigue analysis of welded structural components is based on the $S-N$ curve based on full scale testing of specific welded details which presumably contain residual stresses and minor flaws. This appears in codes such as BS5400⁴. Fitness for purpose can be assessed using fracture mechanics codes such as BS7910⁵. In that code, residual stress without PWHT should be taken to be the yield stress, but a lower residual stress of 30% yield may be assumed after PWHT

Residual stresses in weld joints can be reduced by heat treatment⁶ or by mechanical stress relieving⁷. PWHT is often referred to as a stress relieving process since it is assumed that residual stresses are reduced by heating the component to 550-650 °C for a period of time depending upon plate thickness, followed by uniform cooling. PWHT is also very helpful because it softens or tempers any hard martensite or bainite that has formed in the heat affected zone (HAZ). However, PWHT does not always have a positive effect and can cause distortion and degradation of the microstructure.

Stress relieving heat treatments are generally avoided unless specified as mandatory by Codes and/or Standards, because of the high cost involved and potential adverse consequence of incorrect PWHT procedure. PWHT is not required on clusters on mining booms (though PWHT is used on butt to butt welds in
the chords) and is often not performed on other civil structures.

There are many methods of residual stress measurements with varying levels of sophistication and complexity\(^8\),\(^9\). Using neutron beams to measure the deformations in the material crystal structures is one possibility\(^10\). Neutron beam measurements can quantify residual stresses not only on the surface but also through the thickness of the material. However, these methods are expensive and have limitations of application due to the size of the equipment used (e.g. access to restrictive geometric locations is difficult). One of the most simple but effective techniques involves using semi-destructive techniques\(^11\) such as the conventional hole drilling technique (“HD”)\(^12\) and ring-core method (trepanning technique), (“TT”)\(^13\).

This paper describes the investigations conducted on microstructure, hardness, tensile tests and residual stress measurements in a mining boom cluster before and after PWHT. Experience with the use of incremental hole drilling technique for residual stresses measurements in the clusters is described. The results are considered in relation to the fatigue performance of the connections with and without PWHT.

### 2. EXPERIMENTAL PROCEDURE

#### 2.1 Material Properties

The cluster design involved is an overlapped multi-planar K-K- tubular welded connection (Figure 1), consisting of 406 mm (16’’), 19 mm thick main chord and four lacing members of 168 and 219 mm (6’’ and 8’’) OD and 8 mm thickness. The parent material for this construction is carbon steel, the typical chemical composition of this material and the weld metal are shown in Table 1. The typical mechanical properties of the parent metal for a main chord and lacings are shown in Table 2. The typical microstructures for the parent material, HAZ and weld metal after PWHT are shown in Figure 2. Note that these show no noticeable variation to the observations of microstructure that have been made on this and other clusters prior to PWHT.

After the root bead, the welding on these clusters is performed by the weaving technique. The welds conform to AWS D1.1\(^14\).

#### Table 1. Typical chemical composition of weld and parent material

<table>
<thead>
<tr>
<th>Material</th>
<th>% C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Cu</th>
<th>V</th>
<th>Ti</th>
<th>Co</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent</td>
<td>.19</td>
<td>.22</td>
<td>.96</td>
<td>.01</td>
<td>.02</td>
<td>.08</td>
<td>.10</td>
<td>.03</td>
<td>.07</td>
<td>.08</td>
<td>.01</td>
<td>.01</td>
</tr>
<tr>
<td>Weld</td>
<td>.07</td>
<td>.46</td>
<td>1.5</td>
<td>.02</td>
<td>.01</td>
<td>.04</td>
<td>.03</td>
<td>.31</td>
<td>.15</td>
<td>.01</td>
<td>.01</td>
<td>.01</td>
</tr>
<tr>
<td>Spec API 5L 60X max</td>
<td>.24</td>
<td>1.4</td>
<td>.025</td>
<td>.015</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Nb+V+Ti &lt; .15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Table 2. Typical mechanical properties obtained experimentally

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>Yield Stress [MPa]</th>
<th>Tensile Strength [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent metal - main cord Before PWHT</td>
<td>330</td>
<td>519</td>
<td>32</td>
</tr>
<tr>
<td>After PWHT</td>
<td>320</td>
<td>506</td>
<td>33</td>
</tr>
<tr>
<td>Parent metal - lacing Before PWHT</td>
<td>298</td>
<td>463</td>
<td>33</td>
</tr>
<tr>
<td>After PWHT</td>
<td>264</td>
<td>440</td>
<td>30</td>
</tr>
</tbody>
</table>
Figure 1. A cluster BE39

Figure 2. Optical micrographs through welded section after PWHT (B39): parent metal (ferrite & pearlite), in HAZ (predominantly bainite), weld metal (martensite & bainite).
2.2. Post Weld Heat Treatment (PWHT).

The stress relieving procedure was based on the requirements of AWS D1.1 and a proprietary procedure developed by the heat treatment company for the post weld heat treatment of pipe butt welds. The procedure involved uniformly heating the cluster up to 600°C, holding for a period of 1 hour and cooling back to room temperature.

Figure 3 shows a picture of the cluster during the laboratory trials and Figure 4 shows the results from the thermocouple measurements of the cluster during the trial.

Measurements of the movement of the lacing members using dial gauges during the procedure showed a maximum variation of 0.6-0.7 mm between members.

**Figure 3.** Cluster with heating pads and insulation fitted ready for heat treatment

**Figure 4.** Thermocouple readings taken during the laboratory trial.

**Figure 5.** Comparison of the results hardness measurements (using EQUITIP) before and after post weld heat treatment (PWHT)
2.3 Weld hardness profile

2.3.1 Non destructive hardness measurements

Hardness measurements were taken on the surface of the cluster using non-destructive technique. An EQUITIP set-up (accuracy ± 6 LD) was used. The area of the measurement was polished and cleaned with alcohol. Direct measurements in (LD) scale were then converted to Vickers scale (HV) and the result shown in Figure 5.

These measurements were taken before and after PWHT to establish the influence of heat treatment on the hardness of the weldment.

2.3.2 Vickers measurements after PWHT on cut cross sections.

Hardness profiles were measured using a 5 kg indentation load on a cross section of parent metal taken from the main cord after PWHT. The line scans (Figure 6a) were taken according to the Australian standard for hardness assessment of weldments\textsuperscript{15}, three impressions in the weld and then every 0.5 mm through the HAZ and the PM. Result are shown in Figure 6b. This information was obtained to establish the hardness of the weld bead and the HAZ.

![Figure 6](image_url)  
**Figure 6** a) Schematic illustration of Vickers Hardness measurements, b) comparison of the results of hardness measurements for line scans.

3. RESIDUAL STRESS EVALUATION

The hole drilling method is often described as “semi-destructive” because the damage that it causes is localized and in many cases does not significantly affect the usefulness of the specimen. The hole drilling method involves the application of a special three-element strain gage rosette (as shown in Figure 7) onto the surface of the component at the measurement location. A small hole (1-2 mm diameter) is then made into the component through the centre of the rosette. The production of the hole in the stressed component causes a redistribution of strains to occur near the hole, which can be detected and measured by the surface mounted strain gauge rosette. The measured relieved strains due to the hole production are then related to the original surface residual stress.

A high speed air turbine assembly (Figure 8) was used for the hole drilling and measurement were taken using strain indicator P-3500 from strain gages type EA13062RE120 with characteristic parameters: resistance = 120 ± 0.2 Ohms, and gauge factor = 2.08 ± 0.01.

The measurements were performed on the cluster according to the method described in ASTM Standard E837\textsuperscript{16}. Incremental readings were taken at steps of 0.5 mm. The location of the measurements before and after PWHT is shown on Figure 9.

The residual stresses were derived using Equation 1 with Young’s modulus taken to be 207 GPa, and Poisson’s ratio 0.3.
\[
\sigma_{\text{max}} \sigma_{\text{min}} = \frac{\varepsilon_2 - \varepsilon_1}{4A} \pm \frac{\sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2}}{4B}
\]

\[
\bar{A} = \frac{1 + \nu - a}{2E}
\]

\[
\bar{B} = \frac{1 - b}{2E}
\]

Equation 1

Where \(\sigma_{\text{max}}, \sigma_{\text{min}}\) are the principal stresses \(\bar{A}, \bar{B}\) are calibration constants; and \(\bar{a}, \bar{b}\) are material independent coefficients. \(\varepsilon_1\) and \(\varepsilon_3\) are hoop and axial strain and \(\varepsilon_2\) is at 45° to these axes (See Figure 7).

4. RESULTS

4.1 Residual stress

The residual stress measurements taken using the hole drilling technique (HD) are shown in Table 3 before PWHT and in Table 4 after PWHT.

Figure 7. Strain gauges geometry and position according to the direction of stress

Figure 8. Hole-drilling measurements on B39 cluster
Table 3. The residual stress measurements using HD before PWHT

<table>
<thead>
<tr>
<th>Gauge No.</th>
<th>Location of the strain gauge</th>
<th>θ angle to the σ_max</th>
<th>Stress (MPa)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>the reference point 880 mm from the cluster centre line</td>
<td>-84</td>
<td>50</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>the centre of the hole 12 mm from the toe of the weld</td>
<td>2</td>
<td>159</td>
<td>66</td>
</tr>
<tr>
<td>3</td>
<td>the centre of the hole 10 mm from the toe of the weld</td>
<td>-13</td>
<td>156</td>
<td>62</td>
</tr>
</tbody>
</table>

Table 4. The residual stress measurements using HD after PWHT

<table>
<thead>
<tr>
<th>Gauge No.</th>
<th>Location of the strain gauge</th>
<th>θ angle to the σ_max</th>
<th>Stress (MPa)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1'</td>
<td>the reference point 720 mm from the cluster centre line</td>
<td>63</td>
<td>56</td>
<td>-58</td>
</tr>
<tr>
<td>2'</td>
<td>the centre of the hole 12 mm from the toe of the weld</td>
<td>-72</td>
<td>99</td>
<td>-35</td>
</tr>
<tr>
<td>3'</td>
<td>the centre of the hole 10 mm from the toe end of the weld</td>
<td>-76</td>
<td>108</td>
<td>-25</td>
</tr>
<tr>
<td>4'</td>
<td>the centre of the hole 12 mm from the toe end of the weld</td>
<td>-23</td>
<td>33</td>
<td>7</td>
</tr>
<tr>
<td>5'</td>
<td>the centre of the hole 12 mm from the toe end of the weld</td>
<td>-23</td>
<td>47</td>
<td>20</td>
</tr>
<tr>
<td>6'</td>
<td>the reference point 720 mm from the cluster centre line</td>
<td>30</td>
<td>20</td>
<td>-41</td>
</tr>
</tbody>
</table>
5. DISCUSSION

5.1 Material properties

Microstructure does not change significantly after PWHT (Figure 2). The Yield strength was reduced by 3% for the main chord and 11% for the lacings, however it still complies with the specifications.

Surface portable non-destructive hardness measurements (Figure 5) and Vickers hardness measurements (Figure 6b) are in good agreement. After PWHT softening in the parent metal (5%) and in the weld (up to 25%) has been observed (Figure 5).

It is to be noted that the high hardness on the surface of the weld before PWHT indicates quite severe cooling conditions in the last bead. The hardness permitted under the Australian Standard for Structural Steel Welding is a maximum of 350 HV 10 in the heat affected zone and weld metal may not exceed parent metal by more than 100 HV 10. This weld does not conform to either of these requirements. Having said this it is to be noted that the hardness tests are not normally conducted on the surface of the weld (though this possibility is not specifically excluded in the standard).

The results from four line scans (Figure 6b) show that the hardness in the HAZ after PWHT does not exceed 250 HV. The root scans (2 and 3) are slightly lower in the weld than the toes scans (1 and 4). This can be explained by rapid cooling in the last weld bead, particularly for scan 4. Using understanding gained in work on neutron beam measurement of multi-bead welds it is probable these results can be explained by rapid cooling of the last metal to solidify.

5.2 Residual stress and extension of fatigue life.

The welded construction of the cluster is highly restrained and is rapidly cooled. This means that the weld is likely to have high residual stresses before heat treatment. Measurements of residual stress were taken close to the welded region for the main chord before (Table 3) and after (Table 4) the heat treatment procedure. The measurements verify that stress levels in the axial direction were reduced by approximately 40% while tensile stresses in the hoop direction were removed or made compressive.

Reduction in residual stress is believed to help prolong the fatigue life of the structure, since high tensile surface residual stress levels are known to contribute to crack initiation and propagation. In reference evidence of this is presented based the fatigue analysis program NASGRO. For the clusters in question fatigue life may be extended from a few years to over 20 years.

6. CONCLUSIONS

This paper investigates the possibilities of using post weld heat treatment (“PWHT”) for reducing residual stress and hardness and thus improving the fatigue life of welded tubular structures. The paper uses a number of non-destructive and semi-destructive techniques to follow the changes in properties during PWHT.

Key findings are that:

(a) Axial residual stresses up to 50 MPa were observed in the seamless cluster chord 880 mm away from any welding. These are presumably stresses left over from original manufacture of the chord.

(b) Residual stresses of 158 MPa were observed 12 mm from the weld prior to PWHT. This is approximately 50% of the yield stress of the material.

(c) Hole drilling is actually not very good at measuring the detail of residual stresses where there is a rapidly changing stress field. The gauges used in the hole drilling technique (Figure 7) prevent the hole being placed closer than about 10 mm to the weld. From neutron beam measurements it is known that the tensile residual stress actually in the HAZ next to the weld can exceed yield and that the stress rises rapidly in the last 5 mm [10 and 18]. This indicates the limitations of the use of the hole drilling technique in regions of fast changing residual stress and what corrections need to be made when no alternative to hole drilling exists.

(d) Stress relieving can significantly reduce (~40%) axial tensile residual stresses around the cluster while tensile stresses in the hoop direction were reduced or made compressive.

(e) High hardness measurements were observed on the surface of the weld metal prior to PWHT. The location of these high hardness measurements conforms to the position of the last bead to solidify. These hardness measurements exceeded the permitted values in the Standard. Arguably, the weld nevertheless may conform to the standard since methods were used to measure hardness that are not normally used in the standard procedures.

(f) After PWHT, hardness was reduced to levels acceptable in the standards.

(g) Reduction in the values of residual stress and hardness which occur during PWHT are likely to improve the service life of the cluster.
Acknowledgements

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References