Non-destructive testing of fatigue specimens of a welded bucket wheel excavator

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Visual testing, liquid penetrant, magnetic particle inspection and ultrasonic testing, were conducted to reveal any defects present in welded tensile and fatigue specimens prepared using the same steel material and welding method as the one used in the manufacture and repair procedures of a KRUPP SchRs 600 bucket wheel excavator. The chemical composition, the mechanical properties, tendency to cracks and the microstructure of the bucket wheel material were determined using appropriate tests.

The initiation of cracks and their subsequent growth during fatigue testing of the welded specimens was studied using non-destructive testing and a metallographic examination in order to investigate the causes of failure during service and predict fatigue life of the bucket wheel welded parts. It was found that the welding method used produces welds with numerous discontinuities that can only be detected using ultrasound techniques.

Key words: bucket wheel, welding, fatigue, non-destructive testing

Introduction

Bucket wheel excavators (BWE) present the backbone of the open pit coal mining system. When in working mode, they are exposed to significantly strong dynamic loads. Continuous exploitation in harsh working conditions provides fertile ground for the occurrence of fatigue cracks. Various non-destructive testing methods have been used to inspect welded joints of BWE’s [1, 2]. Radiographic testing (RT) of a butt welded joint, was used to identify the gas pore type flaws and the linear and isolated slag inclusions which are not within the limits of acceptability for a welded joint [1]. Ultrasonic testing (UT) was conducted, and revealed indications of inhomogenities of a local character, as well as indications of inhomogenities with depicted frequency, which were also unacceptable [1]. After dismantling the fixed and moving pulley blocks the magnetic particle inspection (PT) of the fillet welds was carried out according to the code. Crack indications were observed on all pulleys. These cracks appear more forcefully on the welded joints of the spokes and rim than the welded joints of the spokes and hub [2].

The chemical composition and mechanical properties, the impact toughness, hardness, tendency to cracks and the microstructure of bucket wheel materials were determined using appropriate tests [3]. Furthermore, high values of residual stresses, as well as the cold cracking observed on the welded joint of the knife and the bucket body, suggest that the ‘manufacturing-in defects’ also played a significant role in the failure [3, 4].
The present case study is concerned with investigating the reasons for failure of welded joints in the rim and supporting diaphragms of a KRUPP SchRs 600 bucket wheel excavator. Visual testing, liquid penetrant, magnetic particle inspection and ultrasonic testing, were conducted to investigate for defects present in welded tensile and fatigue specimens prepared using the same steel material and welding method as the one used in the manufacture and repair procedures of the excavator. In addition, the initiation of cracks and their subsequent growth during fatigue testing of the welded specimens was studied using non-destructive testing. A metallographic examination was carried out in order to study the microstructural changes during welding that may be the causes of failure during service of the bucket wheel welded parts.

**Experimental**

The steel material, St52/ S355, was provided by the Kardia Lignite Mine, Western Macedonia Lignite Centre and is the same as that used in the manufacture and repair procedures of the Bucket Wheel (BW) under investigation.

Two types of tensile and fatigue specimens were prepared using the same plain carbon steel material as that used in the manufacture and repair procedures of the Bucket Wheel (BW) under investigation a) Flat (butt welds) [300×50×8 mm] specimens, b) Cross type (fillet cruciform joints) [(2×150) ×50×8mm, cross 50mm], specimens, Figure 1.

![Figure 1. Flat and Cross type tensile and fatigue specimens](image)

They resembled the welded parts of the BW shown in Figures 2 and 3.

![Figure 2. The BW and the parts prone to failure and replacement](image)
The welding method and the welders were the same as those used in repair procedures of the Bucket Wheel (BW) at the Cardia Mine. Manual metal arc was used with two types of 2.50×350mm electrodes to prepare two sets of specimens a) Flat specimen set 1 and Cross specimens, electrode type EN ISO 2560-A: E42 3B 42 H10 and b) Flat specimen set 2, electrode type: EN ISO 2560-A: E42 5B 42 H5. The chemical compositions and mechanical properties of the two types of electrode are shown in Table 1.

Table 1. Electrode characteristics.

<table>
<thead>
<tr>
<th>Electrode type</th>
<th>%C</th>
<th>%Si</th>
<th>%Mn</th>
<th>UTS (MPa)</th>
<th>Y.S. (MPa)</th>
<th>%E</th>
<th>Impact Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-20°C</td>
<td>-40°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E42 3B 42 H10</td>
<td>0.07</td>
<td>0.50</td>
<td>0.90</td>
<td>530</td>
<td>460</td>
<td>28</td>
<td>120</td>
</tr>
<tr>
<td>E42 5B 42 H5</td>
<td>0.08</td>
<td>0.40</td>
<td>1.20</td>
<td>560</td>
<td>460</td>
<td>27</td>
<td>160</td>
</tr>
</tbody>
</table>

High cycle fatigue tests were conducted on welded steel specimen bars to study their behaviour under axial tension loading according to ASTM E 466 using a 100kN capacity Instron machine until cracking or reaching the boundary number of cycles of $10^7$ or $2 \times 10^6$ to save time [5]. Prior to testing any excess weld material was removed by milling using a 45mm diameter 3 cutting edge T25 tool so as to obtain a smooth surface finish and thus prevent the initiation of fatigue cracks from the specimen surface during testing [5, 6].

In order to reproduce the effect of the very high tensile residual stresses that are expected to be present in real welded structures [6] in a small-scale specimen, the testing was carried out under a high stress ratio (R = 0.8) at a high tensile mean. This stringent condition is expected to yield conservative results of the weld fatigue strength [7, 8]. The maximum ($F_{\text{max}} = 100\text{kN}$) and minimum ($F_{\text{min}} = 80\text{kN}$) loads applied were calculated with a maximum stress $\sigma_{\text{max}} = 250\text{MPa}$ (0.8×Yield Strength) and a minimum stress of $\sigma_{\text{min}} = 200\text{MPa}$. Since the cyclic loading waveform shape and a frequency, of up to 100Hz, have no significant effect on fatigue performance in passive environments [5, 6] sinusoidal loading at 50Hz was selected to reduce the testing time and to avoid undesirable out-of-plane bending stresses due to resonance and excessive heating of the specimen.

Hardness and tensile tests were carried out so as to determine the as received, un-welded material properties. The chemical composition of the material was determined using optical emission vacuum spectroscopy and the steel microstructures were studied using optical and scanning electron microscopy (SEM) to investigate the presence of defects or inclusions that could lead to premature
failure during testing. The fracture surfaces of the mechanical tests were further studied with scanning electron microscopy to obtain a better picture of the failure process.

Various methods of non-destructive testing were employed to detect and record any defects present in the welded specimens. All non-destructive testing was conducted by certified researchers. Visual testing was first carried out on flat and cross type specimens to investigate for surface discontinuities using indirect and direct techniques. The areas examined were the lid + HAZ (25mm from either side), as well as the root + HAZ according to ISO EN 17637 [9], and EN ISO 5817 [10] using the appropriate equipment (photometer, ×2-×10 magnifying lens, welding gauge, tape measure, ruler, solvent and cloths. A liquid penetrant investigation followed according to the standards ISO 3452 [11] and ISO 23277 [12].

The specimens were also tested with the magnetic particle method using a Karl Deutsch yoke electromagnet and appropriate sprays according to the ISO 17638 [13] and ISO 23278 [14] standards. Two ultrasound devices, the Karl Deutsch Digital Echograph and the Olympus Epoch1000i were used to investigate for subsurface defects. The audit was conducted in accordance with ISO 17640 [15] and ISO 23279 [16]. The initiation and development of cracks during fatigue testing was studied using ultrasound non-destructive testing.

Results

The chemical analysis of the material showed that the material was a plain carbon steel (0.17 %C, 0.3%Si, 0.45%Mn, 0.04%P, 0.04% S), common in the manufacture of BW structures. The tensile and hardness properties of the as received un-welded material are shown in Table 3. As can be seen the yield strength is ~300MPa which would class the steel as a St42/S300 according to DIN 17007 or EN 10027. However, the engineers at the Cardia mine believed the material was St52/S355 with a yield strength of 355MPa.

The tensile and hardness properties of the welded material are also shown in Table 3. The values exhibited are very similar to those of the un-welded material and this may be proof of the good quality welding carried out. The variation in material hardness in the welded specimens is shown in Table 3.

A considerable increase in the Vickers hardness (VPN), along the length of the welded specimens, is observed for both sets of specimen. For specimen set 1, from 363 in the base metal, to 464 in the heat affected zone, to 556 in the weld metal and for specimen set 2, from 363 in the base metal, to 442 in the heat affected zone to 520 in the weld metal.

Table 2. Tensile and hardness properties of the un-welded and of the welded material

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Tensile Strength (MPa)</th>
<th>Yield strength (MPa)</th>
<th>% Elongation</th>
<th>Hardness VPN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un-welded</td>
<td>431</td>
<td>297</td>
<td>41</td>
<td>363</td>
</tr>
<tr>
<td>Flat welded</td>
<td>436</td>
<td>298</td>
<td>36</td>
<td>363-464-556</td>
</tr>
<tr>
<td>Specimen set 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flat welded</td>
<td>446</td>
<td>302</td>
<td>30</td>
<td>363-442-520</td>
</tr>
<tr>
<td>Specimen set 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross welded</td>
<td>441</td>
<td>301</td>
<td>36</td>
<td>-</td>
</tr>
</tbody>
</table>

As expected, the un-welded material exhibited a ferrite-pearlite microstructure and no martensite or other phases were present that could lead to premature failure (Figure 4). The microstructural changes present along the length of a welded specimen are shown in Figure 5. There is an initial increase in grain size followed by an area of small grain size leading to a dendritic microstructure in the weld. The microstructures observed are typical of such steels [17], can account for the variation in hardness along the specimen but do not indicate any reasons for premature failure during service.
Figure 4. Steel microstructure, ×400
The characteristic ductile fracture surface appearance of a tensile test specimen is shown in Figure 6. The fracture surfaces observed using scanning microscopy revealed the presence of manganese sulphide inclusions but as this very common in steel [18-20], it is not expected to cause premature fracture.

The findings of the non destructive tests are shown in Tables 3 and 4. Specimens S1-S10 and specimens S1’-S6 refer to flat specimens of set 1 and set 2, respectively.

Table 3. Discontinuities present in specimen set 1 (welded with electrode E42 3B 42 H10)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>VT</th>
<th>PT</th>
<th>MT</th>
<th>UT</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>overlap (lid)</td>
<td>overlap (lid)</td>
<td>overlap (lid)</td>
<td>pore (root)</td>
</tr>
<tr>
<td>S2</td>
<td>spatter and overlap (lid)</td>
<td>overlap (lid)</td>
<td>overlap (lid)</td>
<td>pore (root)</td>
</tr>
<tr>
<td>S3</td>
<td>misalignment</td>
<td>misalignment</td>
<td>misalignment</td>
<td>misalignment</td>
</tr>
<tr>
<td>S4</td>
<td>pore and spatter (lid)</td>
<td>pore (lid)</td>
<td>pore (lid)</td>
<td>pore (pool) and incomplete fusion (root)</td>
</tr>
</tbody>
</table>
Discussion

The metallographic and fractographic investigations carried out showed that the microstructures present and the inclusions contained cannot account for the frequent service failures of the welded joints. However, it seems that poor quality welding may be the cause of the problem. As can be seen, for both specimen sets 1 and 2, all nondestructive testing methods indicate the presence of some type of discontinuity. In particular, for specimen set 1, VT, PT and MT showed the presence of considerable overlapping and misalignment and would have prevented such welds from going into service, according to the standards [11-14]. However, for specimens S4, S6 and S8, UT showed the presence of pores and incomplete fusion which were not detected by VT, PT and MT. In practice, when rim replacement takes place, visual inspection is performed forty-eight hours after welding is completed and liquid penetrant inspection is used only where defects are suspected [21]. This means that, for example, welds containing discontinuities such as those in specimens S4, S6 and S8 would not be detected and the repaired BW would go into operation. Although all samples, even those containing defects performed well under tension, specimens S6 and S8 failed to achieve the required number of cycles ($10^7$) when tested under fatigue.

The initiation and development of cracks, which led to fracture, during fatigue testing in specimens S4, S6 and S8 was studied using ultrasound nondestructive testing. The development of the discontinuities in specimen S8 is described in detail below.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>VT</th>
<th>PT</th>
<th>MT</th>
<th>UT</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1’</td>
<td>overlap (lid)</td>
<td>overlap (lid)</td>
<td>overlap (lid)</td>
<td>pore (pool) and incomplete fusion (root)</td>
</tr>
<tr>
<td>S2’</td>
<td>overlap (lid)</td>
<td>overlap (lid)</td>
<td>overlap (lid)</td>
<td>pore (root)</td>
</tr>
<tr>
<td>S3’</td>
<td>incomplete penetration (root)</td>
<td>incomplete penetration (root)</td>
<td>incomplete penetration (root)</td>
<td>pore (pool) and pore (root)</td>
</tr>
<tr>
<td>S4’</td>
<td>pore (lid)</td>
<td>pore (lid)</td>
<td>pore (lid)</td>
<td>-</td>
</tr>
<tr>
<td>S5’</td>
<td>spatter and overlap (lid)</td>
<td>spatter and overlap (lid)</td>
<td>overlap (lid)</td>
<td>small true relevant discontinuity</td>
</tr>
<tr>
<td>S6’</td>
<td>spatter (lid)</td>
<td>spatter (lid)</td>
<td>-</td>
<td>small true relevant discontinuity</td>
</tr>
</tbody>
</table>

Table 4. Discontinuities present in specimen set 2 (welded with electrode E42 5B 42 H5)
The following discontinuities were observed in sample S8 in the initial ultrasonic testing (Figure 7). A large pore in the root at a depth of 7.8mm and cluster porosity in the pool at depths of 0.8, 1.8 and 2.3mm.

7.8mm

0.8mm

1.8mm

2.3mm
After 1,200,000 fatigue cycles there was a development in the preexisting discontinuities and new ones appeared. Firstly, the cluster porosity developed from depths of 0.8, 1.8 and 2.3mm to 0.5, 1.4 and 1.7mm, respectively (Figure 8).

Secondly, new discontinuities appeared, pores in the pool at 2.6mm and 1mm depth and 2.6mm (Figure 9).
After 2,000,000 cycles the discontinuities observed were as follows (Figure 10). The original pore in the root at a depth of 7.8mm progressed to 7.4mm. The cluster porosity developed from depths of 0.8, 1.8 and 2.3mm to 0.5, 1.4 and 1.7mm after 1,200,000 cycles and at 2,000,000 cycles to 0.5, 0.4 and 1.2mm, respectively.
Figure 10. The original pore and the cluster porosity development in sample S8 after 2,000,000 cycles.

The new discontinuities developed from 2.6mm and 1.0mm to 1.7 and 1.0mm, respectively. Finally, a new, cluster porosity type discontinuity appeared in the weld toe at a depth of 7.8mm, probably due to fatigue crack development (Figure 11).
Subsurface and surface cracks appear at 4,000,000 cycles as shown in Figure 12. Firstly, quite a few subsurface and surface cracks develop from the preexisting pores; a surface crack in the weld pool and a crack in the root at a depth of 0.1 and 7.8 mm, respectively. A number of small cracks in the weld pool at various depths (0.2, 0.3, 0.7, 1.0, 1.1, 1.5, 1.9, 2.3, 3.4, 4.1) and cracks in the toe at depths of 7.3 and 3.9 mm.
7.3mm

Figure 12. Subsurface and surface cracks after 4,000,000 cycles.

At 8,000,000 cycles the following was observed, (Figure 13).
1) The crack in the pool at 0.1mm depth progressed to 0.7mm depth

2) The crack in the root at 7.8mm progressed to 7.3mm,

3) The cluster porosity at 0.7mm developed into a crack at 1.2mm,

4) The cracks in the toe at depths of 7.3 and 3.9mm developed into cracks at 7.6mm and 4.8mm
Specimen S4 did not fail after $10^7$ fatigue cycles even though it contained considerable defects. However, specimens S6 and S8 failed after 5,300,000 and 8,200,000 cycles, respectively. Failure occurred suddenly, which is characteristic of fatigue [22], usually initiating from a preexisting defect and after progressing to a critical length. The question that arises from this observation is why some defective welds fail and some do not and how one can decide which ‘usual’ quality welds are to be allowed to go into service. The issue has been addressed by a number of researchers [23-25] who suggest various statistical evaluation methods for censoring of failed and non failed welds for fatigue strength assessment of welded structures. The use of high frequency mechanical or ultrasound impact, TIG re-melting of welds and weld grinding has been recommended for fatigue strength improvement of welded joints [25-27] and will be studied by the authors in future work.

Conclusions

The manual metal arc welding process used for the welding repairs in the bucket wheel excavator needs improvement as most welds produced contain numerous discontinuities. Even though they may not always lead to fracture they will, in some cases, cause premature failure under fatigue loading. Visual testing (VT) and liquid penetrant (PT) testing is not sufficient to detect serious weld defects and ultrasound testing (UT) should be applied in all cases. Steel material of higher yield strength is suggested to be used as the first step towards improving fatigue strength. Additionally, weld grinding, TIG re-melting and mechanical impact of welds would result in longer fatigue life.

References


