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Stress relieving and its effect on life of welded tubular joints

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ABSTRACT

This paper describes investigations into the fabrication and repair of large welded tubular joints and how the processes used affect fatigue life. Research has been conducted to determine the benefit of local post weld heat treatment (PWHT) of the connections in terms of hardness and residual stress. The use of hole drilling and trepanning techniques for residual stresses measurements in the clusters are described. The results are compared with fitness-for-service assessments and considered in relation to the fatigue performance of the welded connections. Very substantial theoretical improvement in fatigue life can be expected after PWHT.

1. Introduction

Tubular members are often used as key elements of large civil structures. A very good example of this is the boom of a large mining dragline. In a tubular dragline boom structure it has been observed that the main chord will experience a number of cracks during its operation. This occurs even though the main chord is constantly under high compressive stress. The cause of the 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 the cracking. For predicting fatigue life of weldments, previous investigations have developed experimental methods to determine the fatigue behaviour of welded structures at locations of defects [1] and at the weld toes [2].

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 behaviour of welds. In particular, tensile residual stress of yield magnitude may exist in as-welded structures and may cause detrimental effects to the fatigue behaviour. The effect of tensile mean stress on fatigue life has long been recognised and quantified by methods such as the Goodman diagram as reported by Berkovits and Fang [3].

For estimating total life, the normal approach to fatigue analysis of welded structural components is based on *S–N* curves established from full scale testing of specific welded details which presumably contain residual stresses and minor flaws. This appears in codes such as BS5400 [4]. Fitness-for-purpose can be assessed using fracture mechanics codes such as BS7910 [5].

Residual stresses in weld joints can be relieved by heat treatment [6] or by mechanical stress relieving [7] to extend the fatigue life of the welded joints. Therefore, some researchers [8–10] worked to control welding residual stress with welding processes and post weld treatments. The most common post weld heat treatment (PWHT) is often referred to as a stress

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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 main 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 (Withers and Bhadeshia [11], Bahadur et al. [12]). Many researchers studied the techniques used to measure residual stresses using non-destructive techniques (such as conventional X-ray [13], synchrotron [14,15] and neutron [16–18] diffraction or ultrasonic examination [19]) and destructive (such as slitting [20], hole drilling [21–23], deep hole drilling, contour method [24]). One of the most simple but effective techniques involves using semi-destructive techniques such as the conventional hole drilling technique (HD) [21–23] and ring-core method (trepanning technique (TT) [25]).

Theoretical and numerical research has been carried out in recent years to study the residual stress distribution around weldments [26–28]. Using both an advanced computational model and experimental data, Dong et al. [29] showed that transverse residual stresses along the weld repair were increased from the residual stress levels of the initial weld. Some researchers also investigated the effect of welding residual stress on fatigue strength of welded joints [30–32]. Hong et al. [30] studied the effect of welding residual stresses on fatigue behaviour of T-joints using a numerical analysis. They found that the residual stresses caused the mean stress, stress amplitude and stress ratio to be changed at a predicted crack initiation site. Ohta et al. [31] evaluated the influence of plate thickness on fatigue strength of butt welded joints. They found that the residual stress of thin welded joints (9 mm thick) was compressive near the plate surface but that of thick welded joints (40 mm thick) was tensile near the plate surface. Ohta et al. [32] also investigated the fatigue threshold and high growth rate regional properties for various welded joints. They concluded that the compressive residual stress is effective to enhance the fatigue strength of welded structures. Kang et al. [13] found that compressive residual stresses near the weld toe surface induced by the welding process had stronger fatigue strength than these welded joints with heat treatment. However, it is well known that a welding process usually generates tensile residual stresses at weld toes and the relief of those residual stresses would augment fatigue strength of welded joints [10,11,33,34].

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 hole drilling and trepanning techniques for residual stresses measurements in the clusters are 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, consisting of 406 mm (16″) OD, 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 microstructures for the parent material, HAZ and weld metal after PWHT are shown in Fig. 1. The typical mechanical properties of the parent metal for a main chord and lacings [35] are shown in Table 2.

2.2. Welding procedure and repairs

Two specific weld procedures have been analysed. These are the cluster welding performed during fabrication and repair welds used to mend cracking in the main chord. Cluster welding is performed utilising the weave technique after first completing a single pass root weld. The finished welds conform to AWS D1.1 [36]. For weld repairs, the preheat and inter-run

Table 1
Typical chemical composition of weld and parent material.

Element	Parent metal	Average content (wt.%) weld metal	Spec API 5L 60X [14] max
C	0.19	0.07	0.24
Si	0.22	0.46	
Mn	0.96	1.50	1.4
P	0.01	0.02	0.025
S	0.01	0.02	0.015
V	0.08	0.01	
Ti	0.01	0.01	Nb + V + Ti < 0.15