Evaluation of Residual Stress Measurements Before and After Post-Weld Heat Treatment in the Weld Repairs

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Abstract

Welding repairs are increasingly a structural integrity concern for aging pressure vessel and piping components. It has been demonstrated that the residual stress distribution near repair welds can be drastically different from that of the original weld. Residual stresses have a significant effect on the lifetime performance of a weld, and a reduction of these stresses is normally desirable. The aim of this paper is to investigate residual stresses in various weld repair arrangements using the non-destructive neutron diffraction technique. This research is focused on characterization of the residual stress distribution: (i) in the original weld; (ii) in a shallow toe weld repair; and (iii) after conventional PWHT. The focus of the measurements is on the values of the subsurface strain/stress variations across the weld.

1. Introduction

In welded structures residual stresses (RS) are formed primarily as the result of differential contractions which occur as the weld metal solidifies and cools to ambient temperature. RS have a significant effect on corrosion, fracture resistance, creep and corrosion/fatigue performance and a full understanding of these stresses is desirable. Therefore, experimental measurements are essential to establish a quantitative understanding of the sign, magnitude and distribution of the RS around the repair, within acceptable limits and to validate increasingly demanding finite-element models. Many non-destructive and destructive techniques are employed for detecting RS in welded components \cite{1}, such as hole drilling, conventional X-ray, neutron (ND), synchrotron diffraction (SD) or ultrasonic examination. Non-destructive measurement is a key issue in the confirmation of the theoretical work. ND is outstanding in its ability to obtain RS non-destructively within the subsurface and interior of components \cite{2,3}.

RS in welded joints and repairs are sometimes reduced by post-weld heat treatment (PWHT) \cite{4} or by mechanical stress relieving. The main aim of PWHT is to reduce or completely relax the RS induced by the welding process. It is an important, but costly step in the manufacture or repair of pressure vessels and pipe components. Stress relieving heat treatments are generally avoided unless specified as mandatory by Codes and/or Standards due to the high cost involved and the potential consequence of an incorrect post-weld heat treatment procedure.

In the work reported in this paper an ordinary quality weld and weld repair in carbon steel (AS 1548-7) were investigated. Detailed residual stress distributions were measured using ND at The Australian Nuclear Science and Technology Organization (ANSTO), Lucas Heights, Australia. The focus of these measurements is on detailed, surface, line scans across the weld, with particular interest in the weld and heat affected zone (HAZ). The residual stress distributions were compared to establish the influence of the shallow repair on the original weld, as well as to investigate the residual stress relaxation after conventional PWHT.
2. Materials and Welding Procedure

Two types of specimens were manufactured, an unrepaired butt weld (Sample I) and the same butt weld with partial penetration repair at the toe of the weld (Sample II). The dimensions of the parent metal plates were the length of 300 mm, the width of 150 mm and the thickness of 12 mm. Both samples were restrained during the welding process. Macrographs of the specimens are shown in Figure 1. Sample I was a 60° preparation butt weld with a 2 mm gap between the plates. Four beads were deposited to fill the weld as it is shown in Figure 1(a). The second weld, Sample II, was produced in the same manner but after the welding, attempts were made to remove a hypothetical crack (4 mm in depth and 60 mm in length) from the HAZ with a 100 mm long repair.

![Figure 1. Macrographs of (a) original weld - Sample I, and (b) repair weldment - Sample II.](image)

| Parameters                        | Root run (1) | Runs (2-6) |
|-----------------------------------|--------------|------------|
| Electrode diameter [mm]           | 1.6          | 1.6        |
| Current range [A]                 | 260-280      | 260-280    |
| Voltage range [V]                 | 28-30        | 28-30      |
| Traverse speed [mm/min]           | 480          | 360        |
| Wire feeding speed [mm/min]       | 3600         | 3600       |
| Electrode stick-out distance [mm] | 20           | 20         |
| Gas flow rate [l/min]             | 20           | 20         |

![Figure 2. Vickers hardness traverses (T) measured before and after post-weld heat treatment (PWHT) for (a) Sample I and (b) Sample II.](image)
The repair comprised two stages, the first being the grinding of the groove to remove the “crack”, followed then by the deposition of the fifth and sixth beads. The welds were produced using a semi-automatic flux core arc welding process. The welding parameters are shown in Table 1. The conventional post-weld heat treatment (PWHT) (at the furnace where the holding temperature was 600°C for 1 hour) was applied to both samples after they were measured in the as-welded condition. Hardness profiles were measured on both samples before and after PWHT (Figure 2). This information was obtained to ascertain the effect of post-weld heat treatment on hardness. No degradation of the parent metal was observed in any sample.

3. Neutron Diffraction Procedure

ND measurements of RS were undertaken on The Australian Strain Scanner (TASS) at ANSTO, Australia. The neutron wavelength used was 1.40 Å. Measurements were made using the αFe (211) reflection, at the detector angle, 2θ, of approximately 73.5° with the scattering vector parallel to each of the three axes identified as longitudinal (parallel to the length of the weld), transverse (perpendicular to the length of the weld and parallel to the plate) and normal (perpendicular to the length of the weld and perpendicular to the plate). The measurements were made in the middle of the weldments across the weld and 2 mm below the surface. The gauge volume for the longitudinal and d₀ measurements was approximately 1.5×1.5×2 mm³ but for the transverse and normal measurements this gauge volume could be relaxed in one direction to 1×1×20 mm³. To establish the “stress-free” lattice parameter, d₀, a “comb” reference sample was produced from an identical weldment. (For more details see [5].) No significant variations were found therefore the average of all measurements across the “comb” reference sample was used to determine the strains at all the points in the weldment. The longitudinal, transverse and normal components of the residual stress field were calculated for each strain-measurement position in the weldment from the relevant three strain components. For this conversion, a Young’s modulus of 207 GPa and Poisson’s ratio of 0.3 were used.

4. Results and Discussion

Figure 3(a) shows the residual stress across Sample I measured by ND. The RS in the longitudinal direction within the weld and at the weld toe are very high, up to the yield strength of the weld material. The transverse stresses are lower, up to 110 MPa at the toe, on the side of the last deposited bead and to -60 MPa on the opposite side. This may be due to the larger size of the weldment which results in a high constraint condition.

After the successful repair (Sample II) a broadening of the peak of the longitudinal residual stress distribution was observed and high RS were found within the weld metal and HAZ, as shown in Fig. 3(b).

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Residual stress distribution across (a) the original butt weld Sample I and (b) repair weld Sample II measured by neutron diffraction (1.5 mm below the surface).
Additionally, following the repair an increase in the transverse stresses was found on the opposite side of the repair, up to 280MPa, at the weld toe.

After the residual stress measurements in the as-welded condition were completed, the PWHT was applied to both samples and the residual stress measurements were repeated. The residual stress distribution across the weld repair, Sample II, is shown in Figure 4. The residual stress significantly decreases in all directions in the weld and parent metal, which proves that conventional post-weld heat treatment is a very effective stress relaxation technique.

![Figure 4](image-url)

**Figure 4.** Residual stress across repair weldment (Sample II) after PWHT (1.5 mm below the surface).

5. **Conclusions**

High longitudinal RS were found within the weld as well as at the weld toe, in the as-welded condition, exceeding the uniaxial yield value of the parent metal. Additionally, in the region of the HAZ the longitudinal residual stress varied rapidly from highly tensile in the weld to a balancing compressive value in the PM. Transverse RS are much smaller in the original weld but they increased significantly after the deposition of the weld repair. Tensile transverse residual stress may be particularly detrimental to the weld life performance, as in many cases in-service stresses will superimpose in that direction. PWHT was very effective in reduction of high RS around the weld and weld repair. Conventional PWHT is strongly recommended for original and repair welds, especially where RS play a role in driving in-service cracking.

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7. **References**

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