Residual stress analysis of friction stir welded AA6063 pipe butt joint by neutron diffraction technique of ENGIN-X

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Abstract. Residual stress refers to stress that remains in a structure when all applied stresses have been removed. It is important because the combination with applied stress can cause failure at the level below at which the failure could occur. A study has been carried out using the non-destructive neutron diffraction (ND) technique of ENGIN-X to quantify the redistribution of residual stresses in a pipe. A three-dimensional residual stress-measurements test is fully performed on a 89 mm (3.5 in) diameter pipe in AA6063 grade aluminium (5 mm wall thickness) containing a girth friction stir weld. The results have shown an opposite residual stress effect due to tool rotational speed increment especially on the retreating side of the weld. This weld residual stress analysis is an important factor for Fitness-For-Purpose Assessments. This residual stress measurement data provides a basis for structural integrity assessment and inspection planning.

1. Introduction

Aluminum alloys are commonly used in railway transport, automobile industries, aerospace, bridges and high speed vessels. It is due to lightweight, with a high strength which is relative to weight ratio, corrosion resistance and ductility. The joining of aluminum is commonly performed in the industry using the arc welding technique but the technique would easily induce severe weld defects and distortion. The friction stir welding (FSW) technique offers excellent mechanical properties and safe to the environment as it produces no fumes and arc, requires no shielding gas and filler metal. In 1991, FSW was invented and introduced by The Welding Institute and was mainly used in welding flat and tubular structures.

Residual stress is the stress that still persists in the structure after all the added load are removed. Stresses due to residuals are easily generated in welded structures. The material’s yield robustness and level of residual stresses may vary. This condition may cause an adverse effect on structural integrity and can cause premature failure [1]. This premature failure may result from the residual stresses when combined with the applied stresses which occur due to the applied stresses. This weld residual stress analysis is an important factor in Fitness-For-Purpose assessments. Similar to the applied stresses, this residual stress can also be determined by the use of proper techniques i.e ENGIN-X [2,3].
A deterioration in the integrity of the structure and performance of the components may persist due to residual stresses in welded structures. Neutron diffraction (ND) is an authenticated approach for the measurement of residual stresses occurring in welds due to its peculiar ability to profoundly penetrate, and map three-dimensional elements. In addition, the scattering neutron beam with bulk dimensions are also averaged on volume. The variations of the residual stress within the nugget zone (NZ), thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ) can be measured using the ND [4-6]. The present study focuses on how the friction stir welding parameters affecting the residual stress of tubular component was measured and analyzed. Figure 1 shows the dedicated ENGIN-X facility at ISIS, UK.

![Figure 1. ENGIN-X Facility](image)

2. Methodology

FSW of relatively small diameter of 89mm aluminum pipes is a relatively new application thus presents a unique challenge which requires the use of specialized techniques and equipment [2,3]. The lab test was conducted at the ISIS STFC neutron diffraction facility (ENGIN-X) in UK. The welding residual stress measurement was characterized in the as-welded pipe specimen (in the hoop, longitudinal and radial directions relative to the pipe), measuring residual stresses at the 45° angle position. The test was performed on full three-dimensional residual stress measurements on 89mm diameter pipe in AA6063 grade aluminium with 5-mm wall thickness containing a girth friction stir weld and weld width of 20mm. The single line scans were performed at this location at 2 mm below the cap level. There were 12 measurement positions along each measurement line extending -20 mm and +20 mm from the weld center as shown in Figure 2.

![Figure 2. ND measurement points on pipe specimen](image)

A set of stress-free (d₀) reference combs from similar locations on a pipe containing a girth weld manufactured using the same welding parameters were prepared as shown in Figure 3. Cross-sectional samples of 4 mm × 5 mm × 100 mm were wire cut along the length of the pipe specimen to serve as d₀ samples [2,3]. The positions where the d₀ samples were corresponded to the ND measurement position.
made on the pipe specimen in order to maintain comparable microstructure distribution. These matchsticks were focused on weld and heat-affected zone regions as well as the base material. The same number of positions were measured on these stress-free combs specimen. The two sets of welding parameters used for these specimens were shown in Table 1 below. The setup of the specimen on the ENGIN-X is shown in Figure 4.

![Image of stress-free comb specimen](image1)

**Figure 3.** A stress-free comb specimen \(d_0\) of pipe

| Specimen No. (SN) | Rotational Speed (rpm) | Travel Speed (mm/s) |
|-------------------|------------------------|---------------------|
| SN.1              | 1000                   | 5                   |
| SN.2              | 1300                   | 5                   |

![Image of ENGIN-X facility](image2)

**Figure 4.** As-welded pipe specimen and comb specimen setup at the ENGIN-X facility

The experiment was carried out using the time-of-flight neutron diffractometer, ENGIN-X at RAL. These 3 strain components (hoop, longitudinal and radial) were measured via the neutron diffraction technique across the thickness of the two \(2\) pipe specimens using \(2\times2\times2\ mm^3\) gauge volume at ambient conditions. The aforementioned procedures were repeated for the \(d_0\) samples cut to obtain the stress-free lattice spacing at the corresponding scanned positions. The total estimated scan time required for the study was \(3\) days. The data analysis was conducted using ENGIN-X OpenGenie software with GSAS (peak positions analyzed with Pawley refinement).

### 3. Results and Analysis

All three residual stress components were measured in this study. Based on Figures 5 and 6, the residual stresses in the hoop direction were maintained low after the increment of rotational speed. In the vicinity of the weld (±4mm from the weld centreline), the residual stresses dropped to a minimum value from yield magnitude. However, the residual stress was quite high on the retreating side, approximately 15-20mm away from weld centreline. The residual stresses in the longitudinal direction decreased in general with the increment of rotational speed except on the retreating side which gave the opposite effect. However, the residual stress on the retreating side was lesser than the hoop direction.

The residual stresses in the radial direction were also low but limited to the vicinity of the weld zone. The distribution of residual stresses before and after straining follows the same trend in the far field especially on the retreating side, approximately 15-20 mm away from the weld centreline. The
retreating side gave higher but opposite readings with increment of tool rotational speed that was due to cold stirring process as compared to the advancing side which gives more heat [7,8].

![Residual Stress Profile of SN.1](image1)

**Figure 5.** Residual stress for tool rotational speed at 1000 rpm.

![Residual Stress Profile of SN.2](image2)

**Figure 6.** Residual stress for tool rotational speed at 1300 rpm

4. Conclusion

This present study reports on the comprehensive 3D measurements of residual stresses in full scale girth welds of pipes. The following specific conclusions are made. With the increment of tool rotational speeds:

a. Residual stresses in the hoop, longitudinal and radial direction were measured at low value in friction stir welded zone.

b. These residual stresses gave a higher magnitude on the retreating side were due to cold stirring effect and uneven heat distribution between these two zones, as the advancing side gave more heat as compared to the retreating side.
Acknowledgement

The authors acknowledge the support of the Science and Technology Facilities Council (STFC) in United Kingdom for their neutron diffraction facilities of ENGINE-X provided and sponsored for this lab testing, RB 1810192 and the travel grant provided by the Universiti Kuala Lumpur (UniKL), PEM No.80 (3/2018).

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