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The effect of heat input on residual stress distribution of steel welds measured by neutron diffraction

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ABSTRACT

Purpose: of this paper is to investigate the effect of increase in the value of heat input due to change in the welding speed and its influence on residual stress distribution in steel weldments.

Design/methodology/approach: The use of the neutron diffraction (ND) technique for residual stress measurements is described. Fully restrained, single-bead-on-plate specimens have been examined. Detailed measurements within a small gauge volume were taken 1.5 mm below the surface, across the sample. In addition, studies of macrostructure and hardness were conducted.

Findings: Residual stresses in restrained welds and weld repairs are very complex. The heat input affects the value and distribution of residual stress in the specimen. This peak stress in all three samples occurred not at the toe, but in the middle of the weld bead, where the yield stress is higher. The transverse residual stresses of around half the maximum value of longitudinal stress have been observed.

Research limitations/implications: Measurements of residual stress can be very expensive and time consuming. The ND technique is capable of non-destructive investigation in a relatively small gauge volume in depth of the material. However, a number of important issues still remain puzzling, including the uncertainties in the measurement, reliability and interpretation of the results, particularly in regards to the sampling volume and generally in the lack of an engineering standard procedure.
The results may be used to calibrate finite element modelling of the welding process.

Practical implications: The findings have important consequences with respect to design of welding procedures and fitness-for-purpose assessments.

Originality/value: The authors have used ND assessment of residual stresses to follow in detail the changes due to heat input in a small gauge volume. This paper could be an interesting source of information for engineers and researchers who work with welded structures.

Keywords: Welding; Residual stress; Neutron diffraction; Heat input

1. Introduction

Welding residual stresses have important consequences on the performance of engineering components. High residual stresses lead to loss of performance in corrosion, fatigue and fracture but as yet these consequences are poorly quantified. Residual stresses arise from misfits in the natural shape between different regions in a component [1, 2]. In welding in particular, residual stresses are formed in the structure as the result of differential contractions which occur as the weld metal solidifies and cools to ambient temperature. Residual stresses in weld joints are mostly reduced by heat treatment [3] or by mechanical stress relieving [1].

The amount of distortion can be minimized by optimising the welding process. The magnitude of stress is a function of the weld deposit size and the effect of shrinkage [5]. Heat input is another essential factor in quality control in arc welding. Heat input is a measure of the energy transferred per unit length of weld. It is an important characteristic because like preheat and interpass temperature it influences the cooling rate which affects the mechanical properties and metallurgical structure of the weld and HAZ and in consequence affects the residual stress distribution in the weldments [6].

There are various ways of measuring or estimating residual stresses, the direct measurements can be either semi-destructive (e.g., hole drilling and indenting [6]) or non-destructive (x-ray (laboratory or synchrotron) or neutron diffraction (ND) [6] and ultrasonic [7]). Finite element approaches have been used for welding but a major review still determined that there remains an “urgent need” [8] to develop the required knowledge. The residual stresses in weld repairs are much more complex and difficult to understand and predict presumably because of the small size of such welds and the high restraint involved.

In this paper, we report experimental ND measurements of weld stresses generated by single-bead-on-plate. The focus is on the value of line scans of the stress (strain) variation on a plane through the middle of the weldment. The effects of heat input on the residual stress distribution are discussed. Additionally, hardness and macrostructure comparisons were performed.

2. Experimenal procedure

2.1. Parent material

The parent material used in this study was a low-carbon steel [11]. The chemical composition of the material and weld metal are shown in Table 1. The dimensions of the plates were 200x100x12mm^3. The typical mechanical properties of parent and weld metal are shown in Table 2.

2.2. Welding procedure

Experimental work was carried out on three specimens. All the samples were fully restrained single bead-on-pate. The restraint was achieved by tack welding the sample (Figure 1) to a very thick steel plate which was cut off after cooling down to the room temperature. The welds were produced using a flux-cored arc welding (FCAW) process. The specimens were mounted under an automatic-speed-controlled welding torch. The welding parameters are shown in Table 3. Table 4 shows the weld geometrical parameters. There was no pre- or post- weld heat (PWHT) treatment.

Transverse sections were taken across the welds in the middle of the plate for all samples. The typical macrographs showing the parent material, fusion line, weld metal and HAZ are shown in Figure 2 surface for each of three samples with different heat inputs (HI).

The hardness profile (HV) was measured using a 5kg indention load and the results are shown in Figure 3. This information was obtained to establish the hardness of the weld bead and the HAZ. The high hardness indicates quite severe cooling conditions in the heat affected area of the weldment.

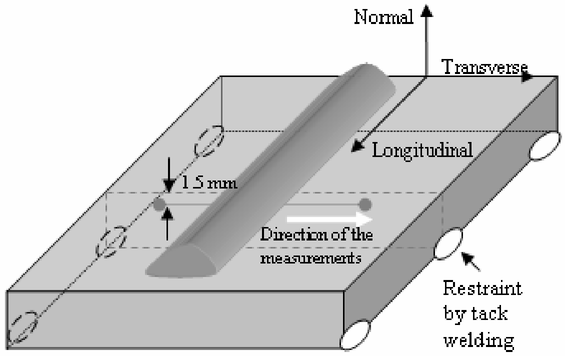

Fig. 1. Illustration of fully restrained single bead-on-plate, showing the direction of the measurements (transverse x, normal y, longitudinal z) using neutron diffraction

Table 1.
Chemical composition of the consumable materials (in wt.%).

Composition	C	Mn	Si	S	P	Ni	Cr	Mo	V	Al
Parent metal	0.12	0.63	0.13	0.01	0.02	0.02	0.01	0.01	<0.01	0.03
Weld metal	0.10	1.7	0.68	0.02	0.02	0.05	0.03	0.04	0.04	

Table.2.
Typical mechanical properties

Mechanical properties	Yield Stress [MPa]	Tensile Strength [MPa]	Elongation [%]
Parent metal (experimental measurements according to AS 1391:1991)	285	429	38
Weld metal (‘as manufactured’ product using Argoshield 52 shielding gas)	445	550	29

Table 3.
Parameters used in the experimental work

Sample	Heat input [kJ/mm]	Traverse speed [mm/min.]	Electrode diameter [mm]	Current range [A]	Voltage range [V]	Wire feeding speed [mm/min].	Electrode stick-out distance [mm]	Gas flow rate [l/min.]
I	0.8	560	1.6	260-280	28-30	3600	20	20
II	1.2	360	1.6	260-280	28-30	3600	20	20
II	1.6	280	1.6	260-280	28-30	3600	20	20

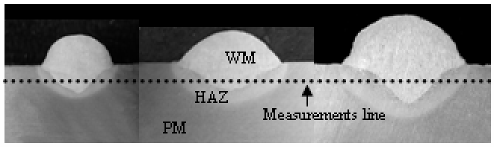

Fig. 2. Optical macrographs through welded section of Sample 2 showing: parent metal, PM, weld metal, WM, and heat affected zone, HAZ

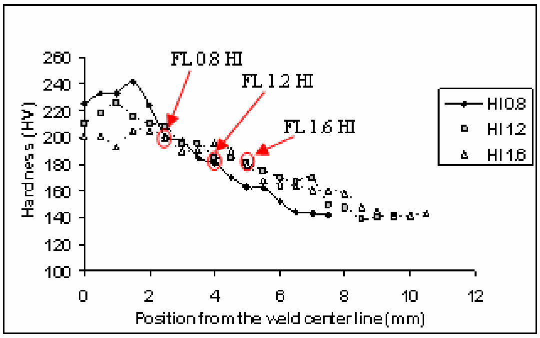

Fig. 3. Hardness profiles 1.5 mm below the surface of the parent material from the center line of the weld x = 0, showing fusion line (FL) for three samples.

Table 4.
Weld geometrical parameters

Sample	Heat input [kJ/mm]	Width [mm]	Height [mm]	Penetration [mm]
I	0.8	9	3	2
II	1.2	14	3.5	2.5
II	1.6	16	4.5	3

3. Residual stress determination

3.1. Residual stress measurements using ND

The neutron diffraction technique is now well-established for sub-surface and interior stress measurements in metallic components [1]. The orientation of the principal strains in any specimen is determined by specimen geometry. The strains (ε_{xx}, ε_{yy}, ε_{zz}) convert to the three-dimensional stress (σ_{xx}, σ_{yy}, σ_{zz}) state. For an isotropic solid, Equation 1 of the form:

$$\sigma_{xx} = \frac{E}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_{xx} + \nu\left(\varepsilon_{yy} + \varepsilon_{zz}\right)\right] \qquad (1)$$

gives stresses in three directions, using σ_{xx} as example, where E is Young's modulus and ν is Poisson's ratio.

ND measurements were undertaken on The Australian Strain Scanner (TASS) at ANSTO, Australia. The same measurement parameters were specified for both specimens. The neutron wavelength used was 1.40 Å. Measurements were made using the (112) reflection, at the detector angle, 2θ, of approximately 73.5°. Measurements were made with the scattering vector parallel to the three axes marked transverse, longitudinal and normal, as shown on Figure 1.

3.2. Measurements of "stress- free" parameter

The measurement of residual strain using the neutron diffraction technique relies on the determination of a change in lattice parameter relative to a reference or supposedly "strain-free" lattice parameter, d_o. Obtaining a relevant reference lattice parameter is an important part of the experiment and for this reason some care was taken to prepare and measure d_o specimens.

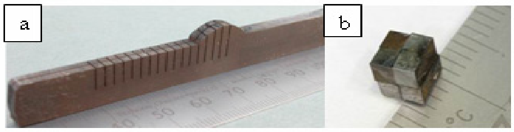

Fig. 4. The specimens a) comb and b) set of cubes used to measure the "the stress-free" parameter, d_o

Two d_o samples, a comb (Figure 4a) and a 4x4x4 mm^3 composite cube (Figure 4b), were produced from Sample II using electro–discharge machining (EDM) with a wire diameter of 0.15 mm. The composite cube was assembled from eight 2x2x2 mm^3 cubes which had been cut from the parent metal and glued together. The comb was made from a section of a fully restrained weldment cut from the middle of the weld, in order to establish any variation in d_o between the parent metal, heat affected zone (HAZ) and weld metal.

Measurements of the d_o for the cube sample were made with the gauge volume positioned in the centre of the cube. For the comb, the centre of the gauge volume (1.5x1.5x2 mm^3) was 1.5 mm below the top surface and in the middle of the weld. The ND measurements of the local d_o show that average differences between the weld metal (d_o =1.18601 Å), HAZ (d_o =1.18600 Å), and parent metal (d_o = 1.18607 Å) are less than 0.0001 Å (±85 microstrain). These data suggest that for this particular alloy and weld, there is no significant effect in the welded region. Therefore, the base-metal, stress-free lattice parameter was used to determine the strains/stresses at all the measurement points in the weldment.

4. Results

The residual stresses were derived from the elastic strain measurements using a Young's modulus of 207 GPa, and Poisson's ratio of 0.3. The results for longitudinal and transverse residual stress components for all three samples are shown in Figures 5 and 6. Error bars are based on the uncertainties in the values of the peak diffraction angle.

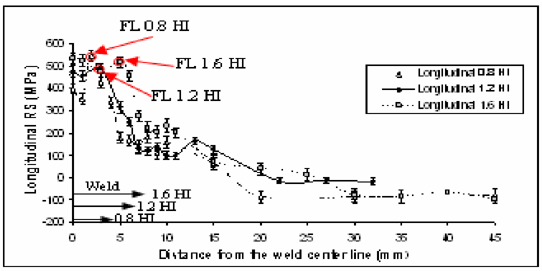

Fig. 5. Longitudinal residual stresses measured by ND against distance from the weld center line. Error bars based on uncertainty in the value of the peak diffraction angle are shown.

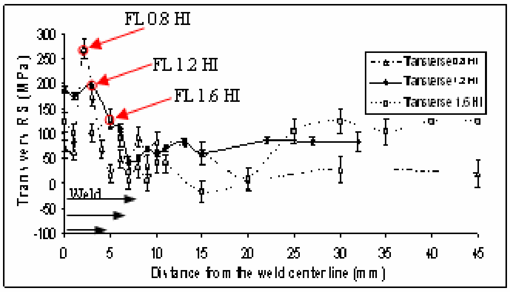

Fig. 6. Transverse residual stresses

5. Conclusions

The use of a neutron beam as a non-destructive method of measuring residual stress due to welding has been explored.

5.1. Macrostructure and hardness

Figure 2 and Table 4 shows that higher heat input enlarges the size of the welds: the higher the heat input, the larger the weld reinforcement and deeper the penetration. Increasing the heat input decreases the hardness in the weld and at the fusion line (FL). Higher heat input slows down the cooling rate which may explain why the hardness at the FZ and the HAZ is lower. Hardness results as shown in Figure 3 indicate significant increases in hardness in the HAZ, with respect to parent metal reflecting higher yield stresses in this region.

5.2. Residual stress

The peak stress in the weld (which is in the longitudinal direction) is significantly higher in the weld area in all samples (Figures 5 and 6), than the specified yield stress of the parent metal in question (250 MPa). They are also higher than the yield stresses of the weld metal (Table II). It must be noted from the stress plots that there is significant hydrostatic tension in the fused zone (100–200 MPa) which means that the maximum principal stresses in longitudinal direction can be higher than yield (reflecting the fact that deviatoric stesses are required to create yield conditions). The peak stress in these cases does not occur under the toe of the weld but in the middle of weld or at the FL. In the transverse direction maximum residual stress of around half of the maximum value of longitudinal stress has been observed at the FL, decreasing in the value with the increasing heat input.

One possible explanation is the especially high quench speeds associated with the fusion line, where the liquid metal is in direct contact with the parent metal. The full exploitation of this kind of information is one key issue in future studies. Our work is currently developing methods of cross checking these results with finite element modelling of the welding process.

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