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Quantification of residual stresses in multi-pass welds using neutron diffraction

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ABSTRACT

Neutron diffraction results highlighted the effect of heat input through changes of travel speed and welding sequence (direction) on the residual stresses in multi-pass weldments of high strength low alloy steel. Residual stresses in excess of yield strength were developed in the weld metal and HAZ particularly for the upper-layers of welds which were not affected by the tempering of the subsequent weld layers. The magnitude of the residual stresses was significantly reduced by increasing the heat input. There was no substantial difference in the magnitude of the residual stresses when the direction of weld deposition was varied but the distribution was more uniform.

1. Introduction

Local plastic deformation resulted from thermal and mechanical processing of fabricated structures is the prime cause of residual stresses generated during a range of manufacturing processes. For welding, the non-uniform temperature distribution and cooling rates are responsible for residual stresses form in welded structures. The nature and magnitude of residual stresses have significant effect on the integrity and life span of welded structures and could be beneficial or detrimental. Barsoum and Barsoum (2009) showed tensile residual stresses reduce fatigue life by increasing fatigue crack growth rate while compressive residual stresses have the reverse effect. There is similar trend for stress corrosion cracking (SCC), as the numerical analysis coupled with experimental work by Mochizuki (2007) confirm higher susceptibility of welded joints to SCC with increasing residual stresses. Cheng et al. (2003) also confirmed the deterimental effect of tensile residual stresses on the structural integrity of welded structures through significant acceleration of the growth rate of the defects, such as micro-cracks and creep voids.

The magnitude and distribution of residual stresses are greatly influenced by the welding procedure and parameters and joint geometry. However, when the effects of individual parameters are scrutinized, there are some contradicting reports generating uncertainty in their applications in real life cases. It is expected the value of heat input to be inversely related to the magnitude of residual stresses where a higher heat input is to result in less stressed weld joint (Jiang et al., 2011). However, since heat input is a combination of welding travel speed, and applied current and voltage, its effects become less straight forward. In other words, the general trend mentioned above may vary depending on the heat input changes originated from changes in welding travel speed or applied current. Ranjbarnodeh et al. (2011) reported that an increase in heat input due to increased current (constant travel speed) reduces the magnitude of longitudinal residual stresses. For travel speed, Peel et al. (2003) showed an increase in heat input due to reduction in travel speed is beneficial in reducing residual stresses in weldment. In contradiction to the above-mentioned studies, Akbari and Sattari-Far (2009), using experimentally validated FEA, demonstrated decreasing heat input due to reduction in current and voltage decreases the magnitude of residual stresses. Numerical simulations by Qureshi (2008) on the effect of weld travel speed ($2\,\mathrm{mm\,s^{-1}}$, $3\,\mathrm{mm\,s^{-1}}$ and $4\,\mathrm{mm\,s^{-1}}$) on residual stresses in a thick-walled cylinder confirmed higher magnitudes of residual stresses at lower travel speed ($2\,\mathrm{mm\,s^{-1}}$), i.e. higher heat input.

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In addition to heat input effects on residual stresses, for multi pass welding which is the theme of this report, the weld sequence including the direction of weld passes could alter the magnitude of residual stresses. Mochizuki (2007) and Deng (2013) studied the effect of the deposition sequence on residual stresses and reported a significant effect on the distribution and magnitude of residual stress. However, there is not much report on the issue of reversing the welding direction effect on the residual stresses although the FEA modelling by Ji et al. (2005) have shown that the peak values of longitudinal and transverse residual stresses decrease by 16.9% and 18.2% in welding in inverse direction in comparison with the welding in the same direction. They did not report any significant changes in the distribution of residual stresses.

Therefore, the main aim of the current work was to investigate the effects of welding heat input (travel speed) and reversing the welding sequence (direction) on the residual stresses in a most common situation of multi-pass welding of high strength low alloy steel.

2. Neutron diffraction

A range of experimental techniques were developed for the measurement of residual stresses and used by different investigators (Javadi and Najafabadi, 2013), ultrasonic, (Sattari-Far and Farahani, 2009), hole drilling, (Mahmoodi et al., 2012), layer removal techniques, (Withers and Bhadeshia, 2001), X-ray and (Pardowska et al., 2008), neutron diffractions. However, as pointed out by Paradowska et al. (2006) the latter technique (neutron diffraction) allows the measurement of residual stresses for most metals and alloys with an effective depth of measurements up to several centimetres, which covers many practical applications including multi-pass welding as the theme of the current report.

Neutron diffraction method represents a non-destructive deep scanning technique for generation of three-dimensional strain maps in engineering components. This method utilises a beam of neutrons with a momentum p, and associated wavelength λ:

$$\lambda = \frac{h}{p} \tag{1}$$

where h is the Planck's constant. When the neutron beam penetrates crystalline materials, a diffraction pattern with sharp maxima is produced. The diffraction pattern can be described in terms of Bragg's law, see Fig. 1 for illustration:

$$2d_{hkl} \times \sin\theta_{hkl} = n\lambda, \tag{2}$$

where d_{hkl} is the lattice spacing, n is an integer number representing the order of the reflection plane and θ is the angle between the incident ray and the scattering planes as shown in Fig. 1. A small change in the lattice spacing (Δd_{hkl}) will result in a change in the angular position of the diffraction peak ($\Delta\theta_{hkl}$) given by the following equation:

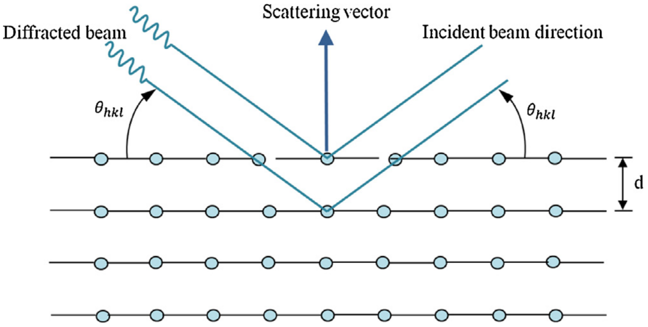

Fig. 1. Schematic illustration of Bragg's law.

$$\Delta\theta_{hkl} = -\tan\theta_{hkl} \times \frac{\Delta d_{hkl}}{d_{hkl}} \tag{3}$$

The lattice normal strain ϵ is given by:

$$\epsilon = \frac{d_{hkl} - d_{0,hkl}}{d_{0,hkl}} = -\Delta\theta_{hkl} \times \cot\theta_{0,hkl}, \tag{4}$$

where $d_{0,\mathrm{hkl}}$ is the strain-free lattice spacing for the *hkl* planes, and $\theta_{0,hkl}$ is the diffraction angle of the unrestrained lattice (Grünitz, 2004).

The strains can be measured in an arbitrary directions and the magnitude of residual stresses can be found using the generalised Hooke's law. In this study, the measurements of strains were conducted in three directions; longitudinal (parallel to the welding direction), transverse (perpendicular to the weld) and normal to the plate (through thickness), as illustrated in Fig. 2.

Details of instruments set up and other general principles of neutron diffraction method can be found in the works done by Park et al. (2004) for T-type and a double V butt joint welded stainless steel specimens and Webster and Wimpory (2001) for different practical welding applications.

3. Experiemental procedures

3.1. Weld deposition

The root pass of all V-prep weld joints was completed with modified short arc welding (MSAW); and flux cored arc welding

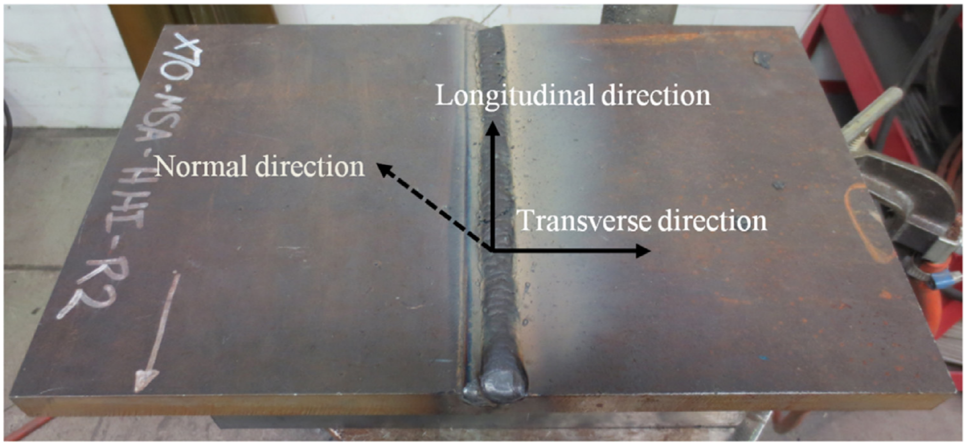

Fig. 2. Welding specimen showing three directions of strain measurements.