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ORIGINAL ARTICLE

Investigation of surface residual stress profile on martensitic stainless steel weldment with X-ray diffraction

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Abstract The development of residual stresses during fabrication is inevitable and often neglected with dire consequences during the service life of the fabricated components. In this work, the surface residual stress profile following the martensitic stainless steel (MSS) pipe welding was investigated with X-ray diffraction technique. The results revealed the presence of residual stresses equilibrated across the weldment zones. Tensile residual stress observed in weld metal was balanced by compressive residual stresses in the parent material on the opposing sides of weld metal.

1. Introduction

The welding of 13% MSS is characterised by phase changes and transformation of austenite, γ to hard and brittle martensite (Griffiths et al., 2004; Spencer et al., 2009; Turnbull and Griffiths, 2003; Woollin et al., 1999). The transformation is accompanied by a significant expansion of up to 1% in volume, coupled with thermal distortion and weld shrinkage, which collectively lead to rise in the level of residual stresses in the pipe (Castro-López and De Cadenet, 1975). Although, the plate like shape of martensite structure has the capability to accommodate the transformation strains and thus provides cushion for this effect (Bhadeshia, 2004; Jones and Alberry, 1978).

Residual stresses occur as a result of misfit between different components in an assembly during manufacturing processes which include welding and fabrication (Thibault et al., 2009). The nature and magnitude of residual stresses in components is dependent on the key material properties namely: coefficient of thermal expansion, heat capacity, density and strength (Bhadeshia, 2004; Mazahery and Shabani, 2013). On a macro scale, the production of seam pipe by progressive folding of plate into circular shape and subsequently welding along the longitudinal axis often introduce residual stresses in the pipe. Whereas on micro scale, microstructures have different responses to temperature change because of the

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difference in their Coefficient of Thermal Expansion (CTE), for instance, the CTE of austenite, γ in steel is about $2.1E{-}06\ K^{-1}$ while that of ferrite, α is approximately $1.3E{-}06\ K^{-1}$ (Bhadeshia, 2004).

Residual stresses introduced by the manufacturing processes can be reduced to minimise their effects during service life. Seamless pipe have little or no internal stresses because of its complementary stress relief annealing during hot working processes. Other methods used include the application of pressurised water to longitudinally welded seam pipe after fabrication (Hanneman et al., 1979) and shot peening using different methods (Dieter and Bacon, 1986; Ling et al., 2008). And, in situations where welding is involved, Post Weld Heat Treatment (PWHT) may be necessary to mollify the consequences of internal residual stresses in the weldment (Dong et al., 2014).

The Gas Metal Arc Welding (GMAW) is one of the welding processes often used for joining martensitic stainless steel pipes to achieve required transportation networks over a long distance (Woollin, 2007; Asahi et al., 1999). It is a very versatile welding process due to the fact that its deposition mode could either be in droplets, spray or globular transfer mode which allows out of position welding to be carried out (DeGarmo et al., 2003; Schmid and Kalpakjian, 2006). In GMAW, the externally supplied shielding gas played dual roles. Firstly, it protects the arc, the molten metal and cooling weld metal from impurities in the air and secondly, it provides desired arc characteristics through its effect on ionisation (Messler, 2008). In addition, welding could be carried out with power source biased towards the DC-Electrode Negative, DC-EN or DC Reverse Polarity, DCRP which is the same as DC-EP mode, depending on the wire used and desired mode of molten metal transfer. The DC-EP is most commonly used because electrons are accelerated from negative work piece onto the positive electrode with sufficient energy to melt the filler wire (Messler, 2008). The aim of this work is to investigate the surface residual stresses in martensitic stainless steel pipe weldment. This was achieved by carrying out surface residual stress measurements on girth welded martensitic pipes, using the X-ray diffraction technique.

2. Experimental procedure

2.1. Materials

The materials used for the research study was low carbon martensitic stainless steels. The materials were provided as-welded by The Welding Institute (TWI), Cambridge, United Kingdom. The original martensitic stainless steel pipe without any welding heat input is referred to as the parent steel and the filler wire used for fabrication was superduplex stainless steel. The detailed chemical compositions of the parent and filler metals are shown in Table 1.

2.1.1. Girth welding of MSS pipes

Mechanised Pulsed Gas Metal Arc (PGMA) welding process was used for the fabrication of the MSS pipes at TWI, Cambridge. The PGMA welding process is notable for significantly lower welding porosity. The Gas-metal arc welding process used 1.2 mm diameter superduplex stainless steel (MW4) (Table 1) as continuous filler wire electrode and an externally supplied inert shielding gases (comprising $Ar/He/CO_2/N_2$) against oxidation and for better control of weld puddle. The consumable wire electrode produced an arc with the work piece which formed a part of the electric circuit and provided filler to the weld joint. Wire was fed to the arc by an automatic wire feeder.

A typical schematic diagram of the weldment is shown in Fig. 1. The three distinct structural zones that exist in the weldment as characterised by the welding heat are: the parent material, the HAZ and the weld metal affected by dilution during high temperature fusion. The transverse sections of girth welded low carbon, MSS pipe was sectioned out for investigation. The sample nomenclature was W2B.

2.2. X-Ray diffraction technique

The $\sin^2\psi$ method of X-ray diffraction technique is applicable for plane stress condition, and was therefore used to determine the magnitude of the residual stress to the depth of about 20 μm in the as-welded specimen. The X-ray diffraction method for lattice strain measurement relies on well established Braggs law illustrated with Eq. (1), where λ is the X-ray wavelength, d is the interatomic lattice spacing and θ is the diffraction angle (Cullity and Stock, 2001; Fitzpatrick et al., 2005).

$$\lambda = 2d\sin\theta \quad (1)$$

The technique measured elastic stress from diffraction elastic constants determined from measurable elastic strains, assuming linear elastic distortion occured in the contributing crystal lattice plane. The lattice elastic strain for the reflections (h k l) at angle ψ are calculated from shift in interatomic lattice spacing (Fig. 2) caused by manufacturing process according to Eq. (2). The lattice spacing, d is obtainable from wave length and diffraction angle, 2θ according to Eq. (2). The d_o is the stress free lattice spacing and the $d\psi$ is the measured stressed lattice spacing (Fitzpatrick et al., 2005).

$$\varepsilon_\psi^{(hkl)} = \frac{d_\psi^{(hkl)} - d_o}{d_o} \quad (2)$$

In plane stress condition (where the in-plane stress, $\sigma_z = 0$) and considering that biaxial stresses exist, then the tensile force which produces a strain along X direction will have a lateral effect consistent with Hooke's law and the ratio of transverse to longitudinal strains defines the Poisson ratio, υ according the Eq. (3)

Table 1 Chemical composition of the specimens used (parent metal and the filler wire).

Description	Element, wt%									
	C	N	Si	Mn	P	Ti	Cr	Mo	Ni	Al
Parent steels	0.009	0.005	0.20	0.43	0.014	0.120	12.20	2.51	6.40	0.03
Filler (1.2 mm ϕ)	0.027	0.232	0.40	0.41	0.016	NA	26.10	3.90	9.30	NA

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