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Investigating the effects of welding process on residual stresses, microstructure and mechanical properties in HSLA steel welds

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ABSTRACT

One of the important steps in the design and fabrication of welded structures is the selection of the welding process and the filler consumables. This is because these two factors control the mechanics of thermal distribution and the chemistry of the welded join, which in turn affect weld integrity through the resulting microstructure and residual stresses. The present study employed neutron diffraction to investigate the effects of welding process on the residual stresses in high-strength low-alloy steel weld joints made by SMAW (shielded metal arc welding) and combined MSAW (modified short arc welding) and FCAW (flux cored arc welding) processes. A significantly higher level of residual stress was found in the MASW + FCAW combination which was shown to be in line with the microstructural and mechanical properties. Higher levels of residual stresses may be related to the formation of bainite and Widmanstätten ferrite in the weld metal and HAZ of the combined MSAW and FCAW processes.

1. Introduction

Welding consumables and welding processes have significant effects on the integrity of welded structures and their performance in service [1–5]. This is because the chemistry of the filler material and the employed deposition mechanics control the phase transformation and thermal distribution in the weld metal respectively. The other important parametric welding setups are the mechanical design of the joint (geometry) and the applied heat input. These are the key factors for the evolution of microstructure and residual stress distribution of the weldments as well as the extent of heat affected zone [6]. The key parameter is the heat input because it determines the peak temperature at each location within the heat affected region as well as the cooling rate. Residual stress is caused by misfits due to different degrees of contraction in different region of the weld and is correlated with the thermal history [7]. The filler chemistry however determines the onset of phase transformation and the associated thermal strain offset by volume increases as detailed in a review study by Withers and Bhadeshia [8].

Amongst a range of welding processes shielded metal arc welding (SMAW) and a combination of modified short arc welding (MSAW) and flux cored arc welding (FCAW) processes are more acceptable routes in fabrication of high-strength low-alloy steel welded structures such as energy pipeline networks, ship building or pressure vessels. Welding with SMAW process offers several advantages including lower equipment cost, portability of equipment, and welding in various positions and confined spaces. If using cellulosic consumables, a faster welding speed and more penetrable welds could be achieved, although hydrogen dissolution may be an issue [9,10]. At the same time using a combination of MSAW and FCAW processes is reported to provide excellent results including ensuring high deposition rate, i.e. improved productivity rates, low distortion and adaptability and ease of use of equipment [11]. For SMAW process, the heat input is usually higher than that of the MSAW resulting in formation of coarser bead structure due to having a slower cooling rate. The wider arc column is another issue for SMAW to induce a wider fusion zone and HAZ [12]. For MSAW, the smaller bead size provides a higher energy density with having less spread of the fusion zone and HAZ along with a comparatively faster cooling rate [12]. This is not the case for FCAW used for fill passes where a higher deposition rate results in lower cooling rate when compared to that of the SMAW process [13]. The lower cooling rate results in FCAW having greater tempering effect on coarse grained heat affected zone (CGHAZ) in contrast to joints fabricated by the SMAW [14,15].

In terms of the welded structure service integrity and performance, SMAW and coupled MSAW and FCAW respond differently. Balasubramanian and Guha [16] investigated the effects of weld-

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ing process on toe cracking behaviour of load carrying cruciform joints. The joints were fabricated from pressure vessel grade steel (ASTM 515 grade F with 0.08–0.22%C and 0.55–1.10 Mn) using SMAW and FCAW processes. It was found that fatigue life is typically longer for SMAW joints than for FCAW fabricated joints. This difference in behaviour was attributed to the fatigue cracks that can easily propagate across a bainitic packet in FCAW with little resistance encountered at low angle boundaries within a pocket. The experimental study also revealed the importance of microstructural characteristics of the HAZ in the fatigue life and toe cracking behaviour of the joints. The findings showed that the HAZ of SMAW contained a low carbon martensitic structure and exhibited better fatigue resistance in comparison with the bainitic HAZ microstructure of FCAW joints. The variation in the microstructure of the HAZ can be explained by the higher heat input employed in FCAW (formation of bainite due to lower cooling rate) which lead to inferior fatigue performance of FCAW joints compared to SMAW joints.

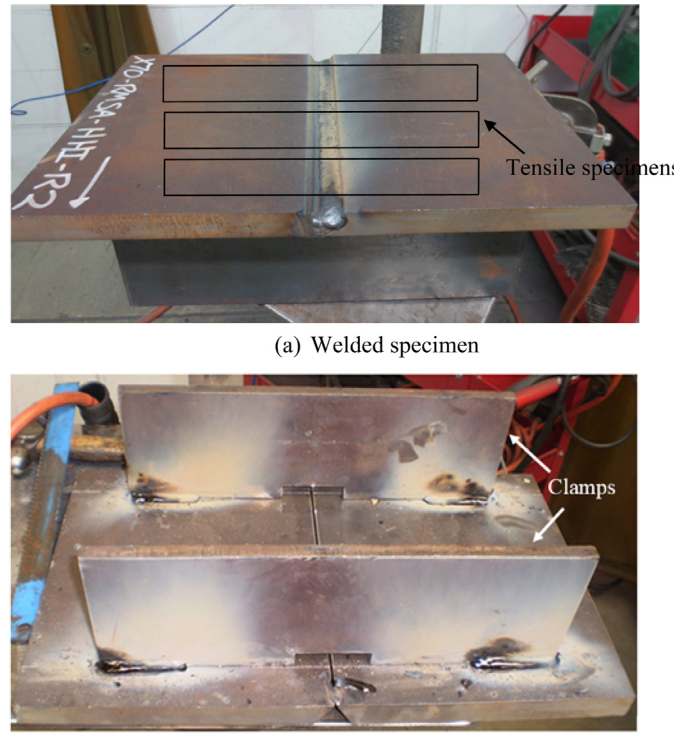
The effects of welding process on the resulting residual stresses and distortion have also been previously studied [14,15]. A range of welding processes including Gas tungsten arc welding (GTAW), also known as TIG, and Activated-TIG (A-TIG), submerged arc welding (SAW), direct current gas metal arc welding (DCGMAW), also known as (MIG), Fronius cold metal transfer (CMT), autogenous laser and hybrid laser welding were used to highlight that both the magnitude and the distribution profile of residual stresses change with welding process [14,15].

As briefly mentioned here, there is no report to examine the benefits and drawbacks of SMAW and combined MSAW + FCAW to eventually arrive at a cheaper and better quality welding process. The current study is therefore carried out to characterize both methods with respect to microstructure, and residual stresses and highlight the ways these factors affect the mechanical properties (hardness and tensile properties) of the welded joint in multi-pass welds. In this paper we present comparative results of microstructural/mechanical property investigations and residual stress measurements for the welded joints fabricated with SMAW and a combination of MSAW for the root pass and FCAW for the remaining passes of multi-pass high-strength low-alloy steel welds widely used in oil and gas pipelines.

2. Experimental procedure

2.1. Details of weld deposition procedure

The test specimens comprised of two 20 mm thick steel plates (API 5L grade X70) with the dimensions of 250 × 200 mm^2. The preparatory joint geometry is shown in Figs. 1 and 3. A total of four samples were fabricated. Two welded samples were used to measure the lattice spacing ($d_{0,hkl}$) in stress free mode and the other two samples were used to evaluate the residual stresses for both specimens. In order to prepare a stress-free sample, both SMAW and MSAW + FCAW specimens was cut in the manner shown in Fig. 2. This is an especial cutting procedure employed, using electro-discharge machining (EDM), to relieve macro-stresses from the weld and HAZ region without introducing new stresses due to cutting [17]. In order to justify the comparison between the two different processes employed in this study, it was tried to have closely possible welding parameters such as heat input and number of weld runs as well as welding consumables with similar mechanical properties. It should be noted that the average heat input for the SMAW and MSAW + FCAW was 0.767 and 0.667 kJ/mm, respectively. However, due to differences in deposition rates (e.g. higher deposition rate with flux cored arc welding) and the arc characteristics it was not possible to have similar number of weld runs. Therefore welding with the FCAW resulted in 25 weld runs along with the MSAW



(a) Welded specimen

(b) Clamp position

Fig. 1. Welded specimen with the applied constraint.

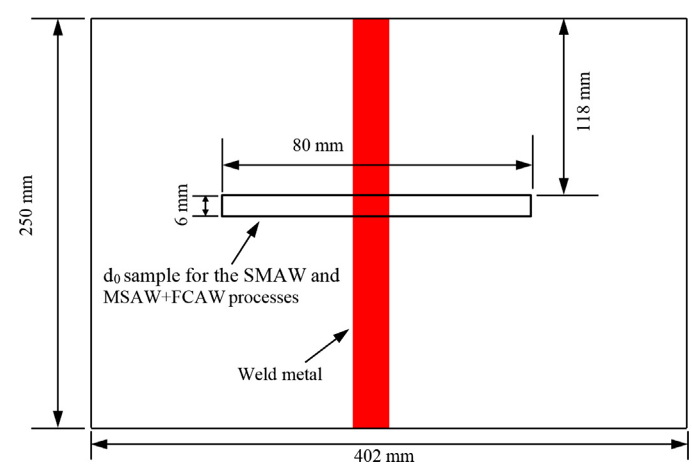


Fig. 2. Schematic drawing of prepared d_0 sample (stress-free sample).

root pass while in SMAW 30 weld runs were deposited for exactly the same joint geometry and size. The welded specimen with the clamp position is shown in Fig. 1.

Specimen series I: The welding process for these samples was SMAW. The weld consumable was specified to be E6010 electrode with a diameter of 3.2 mm for the root pass and E8010 electrode of 4 mm diameter for deposition of remaining passes. Fig. 3 specifies the detailed dimensions of the weld cross section for both samples and the deposition sketch for the SMAW processes. The chemical composition of the weld consumables is given at Table 1.

Also, the details of the welding parameters is given in Table 2. *Specimen series II*: The V-prep weld joints were manufactured using fluxed core arc welding (FCAW) processes with an ER70s-6 electrode for the root pass and modified short arc welding (MSAW) using E81TNi Flux cored wire for the remaining passes. The weld deposition sketch is shown in Fig. 4.