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Influence of microstructural aspects on impact toughness of multi-pass submerged arc welded HSLA steel joints

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ABSTRACT

Multi-pass submerged arc welding was performed on the HSLA steels using multi-microalloyed electrodes in the present work, and three different heat input processes were employed to investigate the microstructure evolution and corresponding mechanical properties of weldments. The emphasis was placed on studying the influence of microstructure aspects on impact toughness of weld metal and HAZ with different heat inputs to reveal fracture micromechanism and to optimize the welding system. According to the experimental results, the acceptable welding parameters were ascertained for the studied steel to obtain a good balance of high strength and toughness welded joint. The optimal range of size distribution of non-metallic inclusion formed in the weld metal was determined and the essential causes of deteriorated HAZ toughness were revealed.

1. Introduction

Since fusion welding was applied in the construction of steel structural engineering, the research emphasis has been placed on the microstructural evolution and performance optimization of welded joints. Because the welding system involves many variables, such as welding processes, process parameters, base metal (BM) and initial microstructures, it is a difficult task to obtain optimal welding system for new steels. As said by Babu [1], the manufacturing community was still shackled by many welding problems even after 100 years of arc welding invention.

In order to meet the requirements of service environment and to lower the cost, many new grade steels with high performance have been developed. Subsequently acceptable welding system should be designed out to ensure the structural integrity of weldments in the practice. However, with increasing BM strength, the strength design of weld metal (WM) is in a dilemma. Traditionally, the WM is expected to have overmatching strength with the BM. Nevertheless, the higher strength WM needs higher alloy content in the welding consumable, which probably leads to lower welded joint toughness, cold cracking as well as higher hydrogen embrittlement susceptibility in the weldment [2–4]. Under some circumstances, the undermatching filler materials to weld high strength steels are preferable, which can improve ductility or be of benefit for structural integrity of weldments [5,6]. These controversies show that welding system design of high strength steel still deserves to be studied.

Many studies focused on the development of high-performance welding consumable, new welding process and welding parameter adjustment for high strength steels in pursuit of optimal welding system [7–14]. Thewlis [7] employed single pass multi-wire submerged arc welding (SAW) to study the weldability of X100 pipeline and considered that the optimum strength and toughness can be obtained in Mo–B–Ti alloyed WMs with predominantly acicular ferrite. However, the WM have undermatching yield strength with the BM. Wang and Liu [9] proposed an optimal composition design for the HSLA-100 steel WMs, i.e. 1.3Mn–2.3Ni–0.55Mo–0.8Cu (wt.%), and 0.03 wt.% niobium was added with copper to develop synergistic precipitation strengthening. They concluded that the WM yield strength can satisfy the 100 ksi yield strength requirement with the 1–2 kJ/mm heat input. Wang et al. [10] also designed high strength WM through nanoscale copper precipitation after reheating to 500–600 °C by subsequent welding pass. Miranda et al. [11] studied the geometry of weld beads and microstructure features of X100 pipeline steel weldments after fiber laser welding and verified the potentialities of fiber laser systems for welding high strength pipeline steels. Other welding methods were also developed to manufacture high strength steel weldment, such as double-sided gas metal arc welding [12] and hybrid laser arc welding [13].

However, the welding problems of high strength steels are far from to be settled. For example, it is known that non-metallic inclusions formed in the WM have two opposing effects on impact toughness. One is the inclusions act as initiation sites for both ductile and cleavage fracture [15,16], the other is that they can assist the formation of

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Table 1
Chemical compositions of the BM, electrode and WM (wt.%).

	C	Si	Mn	Cr + Mo + Cu + Ni	Nb	Ti	B (ppm)	Mg
BM	0.07	0.34	1.65	0.85	0.035	0.025	18	–
Electrode	0.09	0.32	1.87	1.65	–	0.078	10	0.007
WM	0.08	0.50	1.83	1.29	0.012	0.046	12	NA

NA: no analysis.

Table 2
The main welding parameters.

Sample	Current (A)	Voltage (V)	Speed (mm/s)	Interpass temperature (°C)	Number of pass	Heat input (kJ/mm)
1	500–550	26–29	9–10	120–140	7	1.4–1.5
2	600–700	30–35	8–10	130–150	4	2.3–2.7
3	800	36	6.4	130–150	2	4.5

acicular ferrite that is recognized as the most excellent microstructures in the WM [7–9,17–19]. Although some studies showed that the optimal inclusion size should be maintained at about 1.1 μm based on their excellent ability to assist the nucleation of acicular ferrite [18,19], very few is focused on the control of inclusion size in consideration of these two opposing effects at the same time. Additionally, as reviewed by Liu [4], the low HAZ toughness and strength softening zone forming in the HAZ are still the main challenges to welding metallurgists. To deal with these problems, the microstructural aspects in relation to reduced mechanical properties of high strength steel welded joint should be explored deeply, e.g. the effect of microstructural aspects on the fracture micro-mechanism of deteriorated HAZ toughness, and as such will be the focus of this work.

2. Experimental procedures

Base material used in the present study was hot rolled high strength bainitic steel with thickness of 20 mm, which was produced by a thermo-mechanically controlled process. The chemical compositions are listed in Table 1, similar to X100 pipeline steel. The main mechanical properties of BM are as follows: yield strength 750 MPa, tensile strength 930 MPa, elongation 12%, and impact absorbed energy at −20 °C is 196 J.

Welding plates cut along the longitudinal direction of as-rolled steel plate were prepared into the dimensions of 400 × 200 mm. Butt joints with single or double bevel V-type groove were prepared before welding to obtain full penetration of the welded plates with different heat inputs, as schematically shown in Fig. 1. The multi-pass welding experiments were carried out using an automatic SAW machine. Low alloy steel electrode with 4.0 mm in diameter was selected to deposit high toughness WMs due to some intentional additions of microalloyed elements, e.g., titanium and magnesium, assisting the formation of acicular ferrite effectively [20]. The compositions of electrode are also listed in Table 1. An agglomerated commercial flux was used, which contained Al_2O_3, SiO_2, MnO, CaO, CaF_2, TiO_2, and the flux was baked at 350 °C for two hours before welding. Three different heat input processes were designed, the main parameters of which are given in Table 2. During every welding process fine adjustments to welding parameters were conducted to make a good appearance for all weld beads. The WM compositions with middle heat input were determined by spectroscopic analysis using the optical emission spectrometer after welding and are shown in Table 1.

After welding, all tensile and impact specimens were taken from the upper part of weldments along the transversal direction in relation to welding direction (see Fig. 1). Tensile specimens with a gauge diameter of 8 mm and a gauge length of 40 mm were tested at ambient temperature at a crosshead speed of 5 mm/min using a SANS 10 kt servo hydraulic machine. Each process was tested twice and average values of strength and elongation will be reported. To fix the position of Charpy V notch, impact specimens with standard size were macro-etched with 3% nital first to exhibit the outline of HAZ. Fig. 2 shows the partial outline of welded joint with the heat input of 1.43 kJ/mm at low magnification. The location of V notch was determined at the WM or the HAZ near to fusion line as per ISO 9016 standard to examine the WM and HAZ toughness, as schematically shown in Fig. 1. The impact testing was conducted at −20 °C and each condition was examined five times. An instrumental impact tester was employed to record the impact load–deflection curves during impact fracture.

To investigate the relationship between microstructural evolution and mechanical properties of the weldments, metallographic specimens also taken from the upper part of welded joint for microstructure examinations were prepared using conventional methods, i.e. manual and mechanical polishing, 3% nital etching, and hot air drying. Microstructural observations were examined using an optical microscope. Microhardness measurements were made on the cross-section of welded joint using a FM700 hardness-testing machine employed a 0.49 N load. The distribution of non-metallic oxide inclusions in the WM

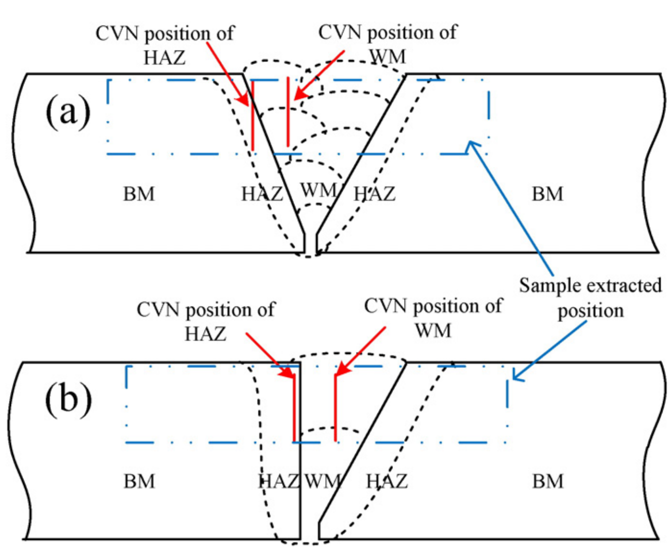

Fig. 1. Schematic diagram showing double (a) and single (b) bevel V-type groove preparation. The extracted position of cross weld samples and CVN position are signified with arrows.

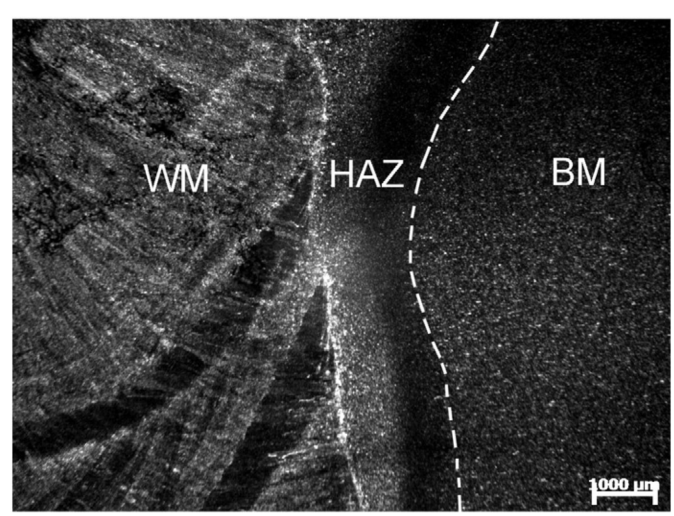

Fig. 2. Partial outline of welded joint with heat input of 1.43 kJ/mm.