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Effect of titanium addition on the microstructure and inclusion formation in submerged arc welded HSLA pipeline steel

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ABSTRACT

The effect of titanium addition on the SAW weld metal microstructure of API 5L-X70 pipeline steel was investigated. The relationship between microstructure and toughness of the weld deposit was studied by means of full metallographic, longitudinal tensile, Charpy-V notch and HIC tests on the specimens cut transversely to the weld beads. The best combination of microstructure and impact properties was obtained in the range of 0.02–0.05% titanium. By further increasing of titanium content, the microstructure was changed from a mixture of acicular ferrite, grain-boundary ferrite and Widmanstätten ferrite to a mixture of acicular ferrite, grain-boundary ferrite, bainite and ferrite with M/A microconstituent. Therefore, the mode of fracture also changed from dimpled ductile to quasi-cleavage. The results showed an increase in the titanium content of inclusions with increased titanium levels of weld metal. Titanium-base inclusions improve impact toughness by increasing the formation of acicular ferrite in the microstructure. No HIC susceptibility was found in the weld metals with titanium contents less than 0.09%.

1. Introduction

The high strength low alloy pipeline steels (HSLA) have a good combination of strength, toughness and weldability. They have been widely used in the construction of long-distance oil and gas transportation systems (Gladman, 1997; Pickering, 1983). Therefore, it is imperative that the steel is characterized by a chemical composition and a microstructure that provide the necessary strength–toughness combination.

Generally, the microstructure of conventional C–Mn weld metals consists of varying amounts of acicular ferrite, allotriomorphic ferrite, Widmanstätten ferrite and microphases, with a yield strength ranging from 350 to 450 MPa. Some high strength low alloy weld metals, such as C–Mn with titanium and/or vanadium and niobium additions, exhibit similar microstructures to the C–Mn welds; however, they have higher yield strength, usually in the range of 500–700 MPa (Bose-Filho et al., 2007). It has been reported that a predominant acicular ferrite microstructure with M/A islands as a second phase, exhibits optimum mechanical properties (Contreras et al., 2005; Junhua et al., 2004; Zhao et al., 2002; Zhao and Yang, 2005; Zhong et al., 2006). To meet simultaneously the requirements of both strength and toughness, a class of more heavily alloyed complex steel welding consumables has been developed.

It has been reported that the weld metal toughness can be increased markedly by an increase of Ni content (Kim et al., 2001). Keehan et al. (2002) found that once Ni exceeds a critical point which depends on Mn percentage; the Charpy toughness at −40 °C is decreased. It was reported by Evans (1998) that the best impact toughness occurred at lower than 0.5 wt% Mo in a controlled manner with respect to Mn content. Also, the addition of Mn and Ni together has been reported to harden weld metal and therefore decrease the impact toughness (Crockett et al., 1995). Conversely, Bhole et al. (2006) found that Mo addition of 0.881 wt% in the weld metal gave the optimal impact toughness at −45 °C with a microstructure of 77% acicular ferrite (AF) and 20% granular bainite (GB).

Like many other alloying elements, chromium produces solid-solution strengthening, although the possibility of precipitation hardening should not be ruled out. It was observed that chromium impaired impact toughness even in the beads with large amounts of acicular ferrite (AF). For high Cr contents, AF is replaced by ferrite with second phase (FS) (Jorge et al., 2001).

Mo and Nb containing steels are commonly used in pipeline applications because it is observed that the HSLA steels containing Mo and Nb exhibit superior strength and toughness combination as compared to the HSLA steels containing Nb and V (Lee et al., 2000; Sun et al., 2002). Manganese is an important alloying element for solid solution strengthening, however reduced Mn content in steels decreases the centerline microstructural banding (Zhao et al., 2003). Also, manganese can affect the transformation of austenite

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Table 1
Chemical composition of the base metal and weld metals.

Composition (%)	C	Si	Mn	P	S	Cr	Ni	Mo	V	Ti	Nb	Cu	Al
Base metal	0.08	0.23	1.55	0.025	0.011	0.17	0.02	0.01	0.005	0.03	0.03	0.006	0.02
Weld no. T00	0.06	0.20	1.90	0.030	0.013	0.08	0.02	0.29	0.008	0.004	0.01	0.03	0.003
Weld no. T10	0.07	0.26	1.92	0.026	0.013	0.08	0.02	0.28	0.01	0.02	0.01	0.03	0.01
Weld no. T20	0.06	0.26	1.99	0.031	0.015	0.08	0.02	0.28	0.01	0.05	0.01	0.03	0.01
Weld no. T30	0.06	0.30	2.15	0.029	0.011	0.08	0.02	0.27	0.01	0.09	0.02	0.04	0.02
Weld no. T40	0.06	0.34	2.23	0.025	0.010	0.08	0.02	0.28	0.01	0.19	0.02	0.05	0.02
Weld no. T50	0.07	0.35	2.29	0.030	0.015	0.08	0.02	0.26	0.02	0.22	0.02	0.05	0.02

Table 2
The consumable materials for the welding process.

Plate thickness (mm)	Electrode type	Electrode diameter (mm)	Flux type
19.8	S2Mo	4	Lincolnweld 995 N

during cooling from high temperatures. Pipeline steels containing low Mn content with additional strength obtained from Cu has been considered for sour service conditions.

Inclusions are known to be an important factor in controlling the microstructure and toughness of weld metals, acting as nuclei for acicular ferrite formation and initiation sites for the cleavage fracture process. Bose-Filho et al. (2007) found that in the weld metals with low Ti content, manganese and silicon were the main chemical elements present in inclusions. Increasing the Ti content in the weld metal leads to an increase in the titanium content of inclusions.

The methodology in the present study consisted of the application of single pass submerged-arc welding (SAW) to produce the welds with different titanium content. This procedure helps us to investigate the effect of different microstructures and inclusion types due to different titanium contents on the properties of the welds. Simultaneously improvement of these factors is beneficial for the application of HSLA steels in sour environments.

2. Experimental procedure

The API 5L-X70 pipeline steel plates were submerged arc welded by using a single pass and similar consumables with different quantities of Fe–Ti powder for designing different chemical compositions of the weld metals. Six groups of specimens with different levels of Ti in the weld metals were made under the same welding conditions. The chemical composition of base metal and the designed contents of Ti in the weld metals are given in Table 1. The consumable materials for the welding process are listed in Table 2. The groove angle and groove depth of the weld joint were 60° and 8 mm, respectively. The additive metal powder used was the Fe–Ti powder with approximately 33% Ti and was fed in the weld joint by a custom-made powder-feeder before the welding was started. The electrical data of the welding process are listed in Table 3. The weld was allowed to cool in air with unfused flux on it for 15 min until the temperature dropped below 200 °C.

Hardness measurements were made with 10 kg load in a straight line 1 mm below and parallel to the surface of the base metal to cover the complete weld metal, heat affected zone and part of the base metal. For each specimen, 6 full-size standard Charpy impact tests were conducted on six welds at each of two different temperatures, namely −10 and −30 °C. Two longitudinal sub-sized standard tensile round samples (6.0 mm diameter of the reduced section and 30 mm gauge length) consisting completely of the weld metal were used in the tensile tests according to ASTM E8.

Optical microscopy and Clemex Imagine Analysis System were used for the microstructural observation and quantitative phase analysis. Also, the microstructural details, type of fracture and composition of inclusions were determined by Tescan Vega II XMU scanning electron microscopy linked to a Rontec EDS system.

Table 3
The electrical parameters of the welding process.

Voltage (V)	Current (A)	Welding speed (cm/min)	Stick out (mm)
30	400	25.4	28

The test method according to NACE Standard TM 0284 (1996) evaluates the resistance of steel to hydrogen induced cracking (HIC). The coupons with 100 mm long × 20 mm wide × wall thickness were cut from the welded plates perpendicular to the weld metal. The test was carried out by immersing specimens in an aqueous solution containing 5% NaCl, 0.5% CH_3COOH saturated with H_2S gas at ambient temperature and pressure. After 96 h exposure in the testing solution, a polished metallographic section of each specimen was inspected for cracks. Three different cracking parameters were measured:

$$\text{Crack Length Ratio (CLR)} = \frac{\sum a}{W} \times 100\% \quad (1)$$

$$\text{Crack Thickness Ratio (CTR)} = \frac{\sum b}{T} \times 100\% \quad (2)$$

$$\text{Crack Sensitivity Ratio (CSR)} = \frac{\sum (a \times b)}{W \times T} \times 100\% \quad (3)$$

where a is the crack length, b is the crack thickness, W is the section width and T is the test specimen thickness.

3. Results

3.1. Metallographic examination

The base metal of all specimens was an API 5L-X70 steel plate contained a typical lamellar ferritic-pearlitic microstructure with

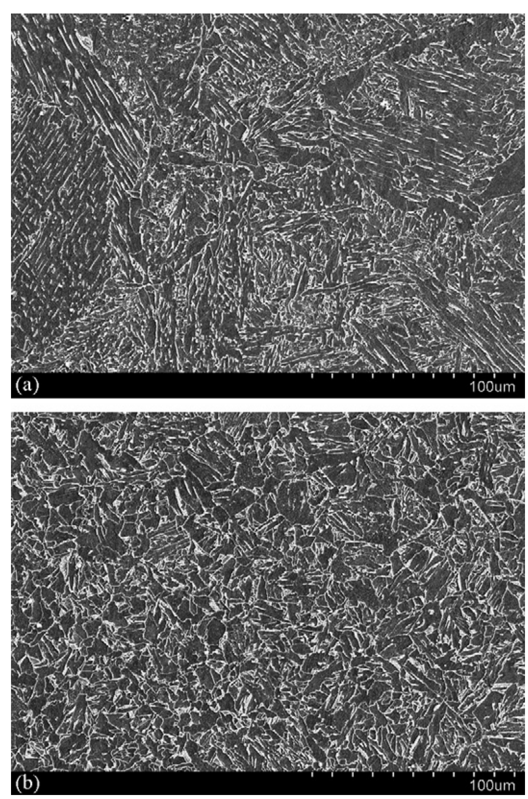

Fig. 1. SEM micrographs of the HAZ microstructure: (a) coarse grained zone; (b) fine grained zone.