



Effect of heat input on microstructure and mechanical properties of dissimilar joints between super duplex stainless steel and high strength low alloy steel



M. Sadeghian, M. Shamanian*, A. Shafyei

Department of Materials Engineering, Isfahan University of Technology, Isfahan 8415683111, Iran

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ABSTRACT

In the present study, microstructure and mechanical properties of UNS S32750 super duplex stainless steel (SDSS)/API X-65 high strength low alloy steel (HSLA) dissimilar joint were investigated. For this purpose, gas tungsten arc welding (GTAW) was used in two different heat inputs: 0.506 and 0.86 kJ/mm. The microstructures investigation with optical microscope, scanning electron microscope and X-ray diffraction showed that an increase in heat input led to a decrease in ferrite percentage, and that detrimental phases were not present. It also indicated that in heat affected zone of HSLA base metal in low heat input, bainite and ferrite phases were created; but in high heat input, perlite and ferrite phases were created. The results of impact tests revealed that the specimen with low heat input exhibited brittle fracture and that with high heat input had a higher strength than the base metals.

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1. Introduction

Duplex (DSS) and super duplex (SDSS) stainless steels consist of approximately equal amounts of austenite and ferrite, which combine the attractive properties of austenitic and ferritic stainless steels such as high strength, highly resistant to chloride stress corrosion cracking, and have excellent pitting and crevice corrosion resistance [1,2].

Due to their corrosion resistance and improved mechanical properties, these steels are extensively used in petrochemical and chemical industries as pipes, pumps, pressure vessels, separators and heat exchangers [3–5]. Moreover, SDSS are widely used in offshore equipment in contact with aggressive chemicals such as H₂S, CO₂, CN⁻ and Cl⁻ [6].

The best properties of DSS and SDSS are obtained with the ferrite–austenite ratio close to 50:50 [1,6]; and detrimental phases such as sigma (σ), chi (χ), secondary austenite (γ_2), chromium carbides and nitrides, which affect the corrosion resistance and toughness in the SDSSs are not present [7].

In welding operations, very low heat inputs lead to high ferrite contents and intense chromium nitride precipitation. On the other hand, high heat inputs and/or long exposure to temperatures in the

600–1000 °C range may cause precipitation of brittle intermetallic phases such as σ or χ [1,7]. In general, welding specifications must be designed to obtain phase proportions (ferrite/austenite ratio) near 1:1 and to avoid σ and Cr₂N precipitation by controlling and limiting the heat input to 0.5–2.0 kJ/mm for DSSs [8] and 0.5–1.5 kJ/mm for SDSSs [9].

With the growing application of new materials and higher demands for such materials, a great need arises for the component or structure of dissimilar materials [10]. Dissimilar joint of SDSS and high strength low alloy steel (HSLA) pipes have been widely employed in the oil and gas industry. Welding dissimilar materials is generally more challenging than welding similar ones because of differences in the chemical, physical and mechanical properties of the base metals welded [7,10]. Therefore, it is critical to understand the heat input–property relationships in joints between SDSS and HSLA. Although certain amounts of research work have been carried out on the microstructure and properties of dissimilar joints between SDSS and HSLA [11–14], no systematic build-up on the effects of heat input on a microstructure and mechanical properties of dissimilar joints between DSS and HSLA has been proposed. Gas tungsten arc welding (GTAW) is the most widely employed joining process in engineering industries, especially in those dealing with structural and piping applications [15]. Therefore, the aim of this study is to investigate the effect of heat input on the microstructure and mechanical properties of dissimilar joints between a SDSS and a HSLA by employing GTAW process.

* Corresponding author. Tel./fax: +98 311 3915737.

E-mail address: shamanian@cc.iut.ac.ir (M. Shamanian).

2. Experimental procedure

The materials employed in this study were API X-65 steel and UNS S32750 SDSS, both supplied in seamless pipe shapes with an internal diameter of 508 mm (20 in.) and a nominal thickness of 4 mm (0.15 in.). The GTAW process with direct electrode and negative polarity (GTAW–DCEN) was chosen for welding because of its flexibility in field applications, which is a necessity in the petrochemical industry [12]. A 70 degree single V groove edge with a root-face gap of 2 mm was employed before welding. Also, an ER25.10.4.L welding rod consumable in two passes was used to join UNS S32750 SDSS grade to API X-65 HSLA grade. The compositions of base metals and filler metal are shown in Table 1. The weld beads were produced in two different heat inputs. Table 2 shows the welding parameters.

In order to investigate the microstructural changes related to welding process, samples were taken from the base metals and the welds. Specimens for the metallographic examinations were prepared using conventional metallographic methods with final 3 μm diamond slurry disc polishing. The etching of API X-65 was carried out using 2% Nital + 4% Picral solution, and an electrolytic etching in 20% Sodium hydroxide (3 V for 5–10 s) was employed for the UNS S32750 and weld metals [16]. This etchant solution is useful for the determination of sigma and chi phases in DSSs (ASTM: A 923-08). The microstructural features then were examined in high-resolution optical microscope (OM) and scanning electron microscope (SEM).

X-ray diffraction (XRD) was carried out on specimens. X-ray diffractometry was done using Philips X'PERT MPD diffractometer with Cu K α ($\lambda = 0.154 \text{ nm}$). Other measured parameters were: voltage 20 kV, current 30 mA, angular interval (2θ) 20–110°, angular step 0.02° and counting time 3 s.

Ferrite number measurements were also carried out using Ferritscope® FMP30 calibrated with secondary standards according to ANSI/AWS A4.2-91 [17].

Microhardness measurements were made across the base materials, heat affected zones and weld metal, and were investigated at 100 g loading in 10 s.

Samples of reduced Charpy size (2.5 mm) were cut from the weld joint, and were machined in accordance with the ASTM:E23-12c standard. Impact tests were performed at $-20 \text{ }^\circ\text{C}$. Macroscopic and microscopic examinations of the fractured specimens were carried out in a stereo zoom microscope and SEM, respectively.

3. Result and discussion

3.1. Microstructures

3.1.1. Base metal and weld metal microstructures

The microstructures of UNS S32750 SDSS and API X-65 steel base materials are shown in Figs. 1(a and b), respectively. UNS S32750

SDSS base material has an elongated grain structure, which is typical in rolled products. This base metal contains 46% ferrite ($\pm 2.5\%$). The HSLA base material has a near-equiaxed grain structure comprised of predominant ferrite matrix with small amounts of pearlite.

The main goal of metallographic examinations was determining the general microstructure of the weld metal and heat affected zones (HAZ) [18]. So, in the metallographic observations, the samples were searched for secondary austenite and intermetallic precipitations. The width of HAZ was also measured, and special attention was paid to seeking any solidification cracking in the weld structure.

General structures of the weld zone in the joints were similar. During solidification of super duplex weld metal, ferrite is the only phase which is solidified. Further cooling in solid state initiates the formation of austenite phase at the delta-ferrite grain boundaries [7]. As can be seen in Fig. 2, austenite and ferrite phases with a dendritic microstructure are caused by fast cooling rates [18]. Austenite and ferrite were distributed uniformly in the weld metal and no detrimental secondary or intermetallic phase was present. Fig. 3 shows the X-ray diffractograms of weld metals. It is clear that detrimental phases are not detected by X-ray diffraction.

The volume fraction of ferrite in weld metals were 44% and 38%. For most industrial applications, austenite contents lower than 25% are unacceptable. Also, for welding and piping inspection, the minimum austenite content should be 30% in the last bead and root passes as a necessary value in order to accept the joint weld [6]. The results indicate that the austenite content of weld metals is accepted, and increases as the heat input increases.

The balance of austenite and ferrite in the weld metal can be controlled in two different ways: adjusting the chemical composition of the weld metal and controlling the thermal cycle of the welding process. Chemical composition can be controlled by selecting the suitable filler metal, which should promote the austenite phase formation in solid state with elements such as nickel and nitrogen [12]. The large amount of austenite in the weld metals is attributed to the chemical composition of filler metals – mainly the Ni element content [11] and the migration of carbon element from HSLA to weld metal. The welding thermal cycles also can be utilized to obtain a favorable equilibrium between austenite and ferrite phases. However, low cooling rates (high heat inputs) may lead to the precipitation of intermetallic phases, and must be avoided [12]. When chemical composition is fixed, the only way to control the austenite/ferrite balance is to control the heat input. The cooling rate is reduced by increasing the heat input [19]. As the heat input increases, the weld metal stays longer in high temperature ranges and more ferrite is transformed into austenite. In this study, the heat input was limited to 0.5–0.86 kJ/mm; so, the precipitation of brittle intermetallic phases was not possible.

3.1.2. Heat affected zone microstructures

Evolution of the HAZ microstructure in welding is more complicated, and depends upon more factors including the original base

Table 1
Chemical compositions of base metals and filler metal (wt.%).

Element	C	Mn	Si	Cr	Ni	Mo	N	Fe	Cr _{eq}	Ni _{eq}	PREN
UNS S32750	0.03	0.82	0.93	25.7	6.3	3.4	0.23	Bal.	29.1	11.95	43.82
API X65	0.26	1.30	0.411	0.016	<0.030	0.049	–	Bal.	0.064	9.2	0.174
Filler metal	0.03	0.73	0.94	25.9	9.2	4.2	0.22	Bal.	30.1	14.65	46.36

Table 2
The welding parameters and the heat inputs.

Sample	Current (A)	Volt (V)	Length (mm)	Time (s)	Speed (mm s ⁻¹)	Heat input (kJ mm ⁻¹)
1	100	15	160	90	1.8	0.506
2	120	16.75	140	100	1.4	0.861

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