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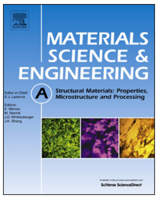

Influence of nickel on the toughness of lean duplex stainless steel welds

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ABSTRACT

Three weldments with the nickel contents 1.3, 4.9 and 6.0 wt% were made from 30 mm LDX 2101® plates. The weldments were subjected to tensile, impact and fracture toughness testing. The aim was to evaluate the susceptibility for brittle failure in the weld metal at sub-zero temperatures (°C). The amount of ferrite was higher for the 1.3 wt% nickel weldment compared to the other two which had similar phase composition and mean free ferrite distance. The result from the tensile testing showed that for the weldment with the highest nickel content the ductility remained unchanged with decreasing temperature while the other two weldments became less ductile with decreasing temperature. *J*-integral based fracture toughness testing showed a significant difference in the susceptibility for brittle failure with higher values for the weldment with 6 wt% nickel than for the others with lower nickel content.

1. Introduction

Wrought duplex stainless steels (DSS) consist of ferrite and austenite, usually in equal proportions. The main alloying elements are chromium, molybdenum, manganese, nickel and nitrogen. The first two elements are ferrite stabilizing while the three later are austenite stabilizing [1]. For the DSS to have high mechanical strength, good toughness, corrosion resistance and weldability a fine balancing between the different alloying elements is needed.

Traditionally these alloys have been used in the offshore industry, the pulp and paper industry and for pressure vessels [1]. Nowadays there is an increasing use of duplex stainless steel in other structural applications due to the maintenance cost savings that come with the corrosion resistance [2]. In particular, lean duplex grades, with lower nickel and molybdenum content, give a competitive cost and are anticipated to be increasingly used for structural applications [3].

Due to the ferrite content the duplex stainless steels exhibit ductile to brittle transitions at sub-zero temperatures (°C). To lower the ductile to brittle transition temperature (DBTT) either the austenite content can be increased or the toughness of the ferrite itself can be raised. Both of these parameters are affected by the nickel content [4–7] which makes the nickel content important for duplex stainless steels toughness. Welding consumables are therefore usually overalloyed with nickel [8] to promote austenite formation in the weldments. Fracture toughness measurements between -110 and -40 °C on the weld metal of the lean duplex LDX 2101® resulted in satisfactory toughness [9,10]. The nickel content in these weldments was in the 8–9 wt% range with ~55% austenite.

The purpose of the present work was to evaluate the influence of nickel on the fracture toughness of welded LDX 2101® duplex stainless steel. Three types of weldments were produced with the aim of having similar microstructure and phase composition but with different nickel contents. The weldments were subjected to tensile, impact and fracture toughness testing between room temperature and -60 °C.

2. Material and welding

The material used in this work was commercially produced duplex stainless steel LDX 2101® (EN 1.4162, UNS S32101) delivered by Outokumpu Stainless AB. The material was hot-rolled to the desired plate thickness of 30 mm followed by solution treating at 1100 °C and water quenching. The chemical composition for the plate and filler metals can be found in Table 1.

The weldments were produced in X-joint configuration where the weldment was parallel to the rolling direction of the parent plates (T–L orientation). A total of 18 beads of filler metal were used and the temperature of the plate was held below 150 °C at all times. The welding parameters can be found in Table 2. The target for the nickel content in the weldments was 1.5, 5 and 7 wt%.

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Table 1
Chemical composition (wt%) of the plate and filler metals. Measured with X-ray fluorescence and combustion analysis.

	C	Si	Mn	P	S	Cr	Ni	Mo	N
LDX 2101®	0.028	0.65	4.95	0.024	0.001	21.5	1.59	0.26	0.22
Autogenous experimental filler, Ø 2.4 mm	0.021	0.74	4.95	0.017	0.001	20.62	1.28	0.10	0.24
Standard commercial filler 23 7 NL, Ø 1.2 mm	0.020	0.50	0.71	0.018	0	23.13	7.30	0.25	0.12

Table 2
Welding parameters for the three weldments.

	Root gap, mm	Land, mm	Groove angle, deg	Heat input, kJ/mm	Current, A	Voltage, V	Welding speed, cm/min
1.3 Ni	0	3.5	90°	1.1–1.3	245–260	30.9	35–42
5 Ni	0	3.5	90°	(1.4) 1.3–1.5	(350) 230–255	(31.9) 32.9	(50) 35–40
6 Ni	2	3	90°	(0.85–1.2) 1.4	(200–236) 350	(25.3–29.9) 32	(27–36.5) 50

* Numbers in parenthesis are for the root when different filler metals or welding methods were used.

Table 3
EDS analysis of the weldments showing the average value. Min–max values in parentheses. Nitrogen and oxygen content measured by combustion analysis.

	Fe, wt%	Cr, wt%	Mn, wt%	Ni, wt%	N, wt%	O, ppm
1.3 Ni	**69.56** (67.84–71.94)	**22.01** (21.33–23.04)	**4.01** (3.53–4.55)	**1.34** (1.01–1.71)	**0.184**	**371**
5 Ni	**69.20** (68.27–70.17)	**22.06** (21.27–22.84)	**3.04** (2.00–3.73)	**4.93** (3.87–5.92)	**0.178**	**348**
6 Ni	**66.89** (64.78–69.35)	**22.92** (21.76–24.14)	**1.47** (0.78–2.31)	**6.02** (5.30–6.63)	**0.137**	**294**

Table 4
Phase composition of ferrite in the weldments. Automatic image analysis based on ASTM E1245 [11].

	α-content, vol%	STDEV 95%	Confidence interval
1.3 Ni	79.6	3	1.2
5 Ni	57.4	7.9	3.3
6 Ni	59.3	7.7	3.6

The welding procedures for these weldments were:

- Submerged arc welding (SAW) with autogenous experimental filler. The low nickel content of this autogenous experimental filler will enable studies of brittle fracture.
- SAW with standard commercial filler for the two root beads where the dilution is high. The remaining 16 beads were submerged arc welded with the autogenous experimental filler and nickel powder additions of 2.5–4.9 g/bead. This configuration enables comparison with the previous low nickel weld.
- Metal inert gas (MIG) welding of the first 7 beads and SAW for the remaining 11 beads. The standard commercial filler metal 23 7 NL was used for both methods. This configuration serves as a reference weld.

For the SAW welding the flux material used had the following chemical composition (wt%): 7 SiO_2, 50 CaF_2, 36 Al_2O_3, 3 Cr.

Result from energy-dispersive X-ray spectroscopy (EDS) across the weldments (through-thickness) is shown in Table 3. Small samples were also cut out from the weld metal of the tested specimens for combustion analysis of the nitrogen and oxygen content. The main differences in chemical composition were in the manganese, nickel and nitrogen content. The weldments are in this paper named 1.3 Ni, 5 Ni and 6 Ni.

For the 6 Ni weldment the manganese content and nitrogen content was likely increased due to dilution with the base metal. For the 1.3 Ni and 5 Ni weldment the nitrogen was however lower in the weldment than in the base metal which can possibly be associated to outgassing of nitrogen during welding.

The phase composition of the weldments can be found in Table 4. The 5 Ni and 6 Ni weldments had similar phase composition but the 1.3 Ni had clearly higher ferrite content. The ferrite content at the root was higher, ~62% and ~63% for the 5 Ni and 6 Ni respectively, compared to the average values in Table 4. For the 1.3 Ni weldment the ferrite content was lower, ~72% at the root weld compared to the average values in Table 4. The likely explanation was that for the 5 and 6 Ni weldments the nickel content was reduced at the root due to dilution with the base metal. The lower energy input in the MIG welding also contributed to the higher ferrite content in the root for the 6 Ni weldment. For the 1.3 Ni weldment the nickel content was instead increased due to dilution (lower nickel content in the filler metal compared to the base metal).

In Fig. 1 representative light optical microscope (LOM) photos of the microstructure for the three different weldments are shown. The microstructure consists of intergranular (grain boundary), intragranular and Widmanstätten austenite in a ferrite matrix. By observing the microstructure in LOM, the 1.3 Ni weldment seemed to have less degree of Widmanstätten austenite compared to the 5 Ni and 6 Ni weldments. The 5 Ni and 6 Ni weldments were indistinguishable from each other. No intermetallic phases were observed.

For duplex stainless base metals with its highly elongated microstructure the austenite lamellar spacing have been found to influence the impact toughness [12] and used for regression analysis of yield and tensile strength [13,14]. For the weld metal the microstructure was more complex so the mean free ferrite distance was used to characterize the weld metal. Line intercept counting with LOM at × 100 magnification on polished and etched samples of the weldments revealed that the 5 and 6 Ni weldments had similar mean free ferrite distance, see Table 5. The much larger mean free ferrite distance for the 1.3 Ni weldments was explained by the higher ferrite phase content.