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Fracture toughness of a welded super duplex stainless steel

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ABSTRACT

Fracture toughness testing was conducted on standard single-edge notched bend bar specimens of base and weld metal. The material was the SAF 2906 super duplex stainless steel. The aim was to evaluate the susceptibility for brittle failure at sub-zero temperatures for the base and weld metal. The base metal was tested between −103 and −60 °C and was evaluated according to the crack-tip opening displacement method. The fracture event at and below −80 °C can be described as ductile until critical cleavage initiation occurs, which caused unstable failure of the specimen. The welding method used was submerged arc welding with a 7 wt% nickel filler metal. The welded specimens were post-weld heat treated (PWHT) at 1100 °C for 20 min and then quenched. Energy-dispersive X-ray spectroscopy analysis showed that during PWHT substitutional element partitioning occurred which resulted in decreased nickel content in the ferrite. The PWHT weld metal specimens were tested at −72 °C. The fracture sequence was critical cleavage fracture initiation after minor crack-tip blunting and ductile fracture.

1. Introduction

Duplex stainless steels are often used in applications that require high corrosion resistance and mechanical strength. Examples are pipelines for the offshore industry, production equipment for the pulp and paper industry and pressure vessels [1]. Nowadays, there is also an increasing use of duplex stainless steel for structural applications, particularly for the grades with lower nickel and molybdenum content [2,3].

The duplex stainless steels are graded from the lean duplex (lower nickel and molybdenum content) to the “standard” grade 2205, then to the super duplex grades and nowadays to the hyper duplex grades. Super duplex stainless steels are defined by having a pitting resistance equivalent number (PRE) larger than 40. The PRE number is defined as a function of the chromium, molybdenum and nitrogen content [1].

The use of the duplex stainless is usually limited to an upper and lower service temperature. At prolonged aging at elevated temperatures (>250 °C) the duplex stainless steels exhibit a ductile to brittle transition with time. A similar ductile to brittle transition also occurs at sub-zero temperatures (°C) where the ferrite becomes increasingly brittle with decreasing temperature. The temperature for the ductile to brittle transition depends for example on the chemical content, the ferrite phase content and microstructure. Fracture toughness testing of lean duplex and the 2205 duplex stainless steel at sub-zero temperatures shows that both the base metal (hot-rolled) and weldments have satisfactory toughness down to −100 °C [4,5].

Sandvik SAF 2906 is a super duplex stainless steel specially suited for applications in caustic environments with a nominal PRE of 41. The nominal composition is (in wt%) 29 chromium, 6 nickel, 2 molybdenum and 0.4 nitrogen. Mechanical properties at room temperature conditions are yield strength of 650 MPa, tensile strength of 900 MPa and area elongation of 25%. The ductile to brittle transition temperature for impact toughness specimens occurs at −100 °C.

The purpose of this work was to evaluate the base and weld metal susceptibly for brittle failure at sub-zero temperatures for the super duplex stainless steel SAF 2906. The methods used were fracture toughness testing on standard single-edge notched bend bars specimens and the use of scanning electron microscopy (SEM) to identify the fracture mechanisms.

2. Material and fracture toughness testing

2.1. Material and welding

The material used in this work was commercially produced duplex stainless steel designated SAF 2906 (EN 1.4477, UNS S32906), produced by Sandvik Materials Technology. The product form was a 200 mm diameter bar that had been solution treated at

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Table 1
Nominal chemical composition (wt%) of the plate, filler metal and the welding flux.

		Fe	Cr	Ni	Mo	Mn	N	Si	C
Bar	SAF 2906	Bal.	29	7	2.2	<1.2	0.4	<0.8	<0.025
Filler metal	Sandvik 29.8.2.L, ⌀ 2.4 mm	Bal.	29	7	2.4	1.0	0.36	0.4	<0.025
		SiO_2	CaF_2	AlO_3					
Welding flux	Sandvik 15 W	7	50	40					

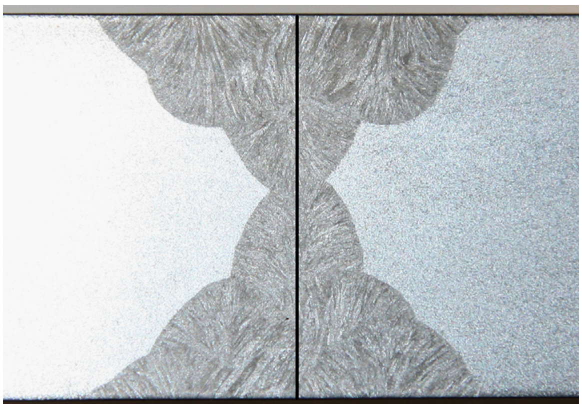

Fig. 1. Cross-section of a weldment. The black straight line shows the location of the notch and fatigue pre-crack.

Table 2
Welding parameters.

Welding method	Root gap (mm)	Land (mm)	Groove angle	Heat input (kJ/mm)	Current (A)	Voltage (V)	Welding speed (mm/min)
SAW	0	4	90°	1.6/1.9	310/360	30	350

Table 3
Amount of ferrite (α) in base metal and weldment. Automatic image analysis based on ASTM E1245 [6].

	α-Content (vol%)	Standard deviation (vol%)
Base metal	51.7	1.6
Weld metal	54.6	1.6

1100 °C and water quenched. 30 mm thick plates were extracted so that the longest side of the plate was parallel to the bar length. The chemical composition for the plate, filler metals and welding flux (which was basic) is shown in Table 1.

The weldment was produced in X-joint configuration, see Fig. 1, where the welding direction was parallel to the grain flow of the parent plates. A total of 12 beads of filler metal were used.

The temperature of the plate was held below 120 °C at all times. The welding parameters can be found in Table 2.

The welded plates were post-weld heat treated (PWHT) at 1100 °C for 20 min. The phase content in the base and weld metal was close to 50% ferrite and 50% austenite, see Table 3.

The microstructure for the base metal consisted of a ferrite matrix with austenite elongated parallel to the grain flow along the bar axis. The orientation of the crack-tip and fracture direction in relation to the microstructure is shown in Fig. 2a. For the weld metal the microstructure can be described as austenite grains in a ferrite matrix, see Fig. 2b.

No intermetallic phases were observed in the base or in the weld metal. In particular, no sigma phase was found.

2.2. Fracture toughness testing

For the fracture toughness measurement, standard single-edge notched bend bars specimens, SE(B), were used. For the base metal specimens, the dimension was $30 \times 60 \times 400$ mm^3 (thickness $\times$ width $\times$ length). For the welded specimen, the dimension was $28 \times 60 \times 290$ mm^3 and the notch-tip was located in the weld metal center line [7] as shown in Fig. 1. Side-grooves were used on all fracture toughness specimens. The crack length (nine point average) divided by the specimen width was (including fatigue pre-crack) 0.54 for the base metal and 0.49–0.51 for the welded specimens. The fracture mechanic testing was made with a 100 kN hydraulic testing machine with a clip-gauge to measure the crack mouth opening displacement (CMOD) of the specimen. The specimens were submerged in ethanol during the testing. Liquid nitrogen was used to cool the ethanol down to the testing

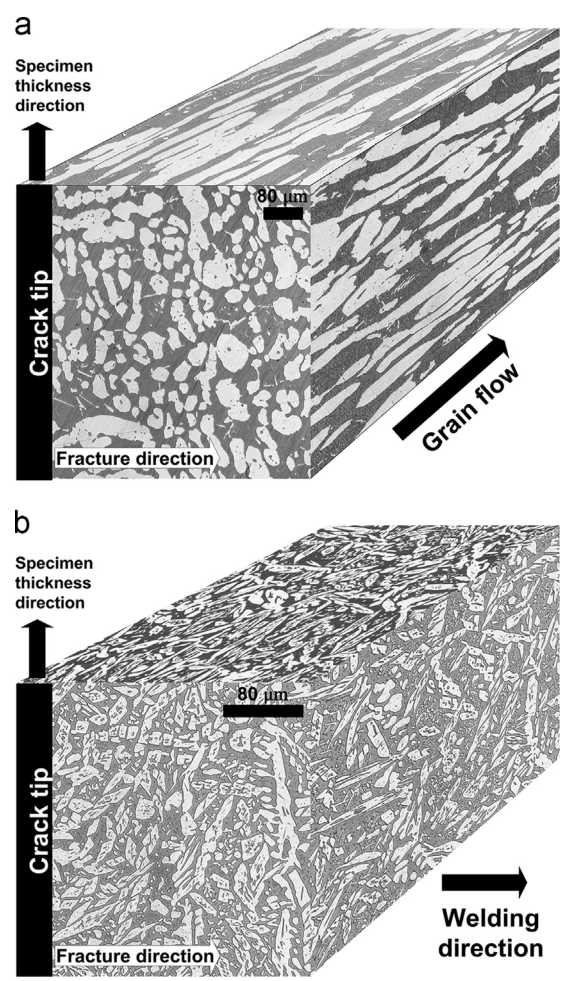

Fig. 2. Pseudo-three-dimensional representation of the microstructure: (a) base metal (100 × magnification) and (b) weld metal (200 × magnification).