

Corrosion Fatigue of X80 weld in Mild Sour Environment

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ABSTRACT

The developments in deep and ultra-deep waters require the application of heavy wall pipes for steel risers in conventional grades. The utilization of higher-strength grade such as X80 reduces the constraints related to the manufacturing and the installation by saving line pipe weight.

Seamless X80 pipes were manufactured in 323.9 x 25.4 mm and characterized. Girth welding was made using the Gas Metal Arc Welding (GMAW) process on these seamless line pipes. Four-point-bend tests were conducted as per NACE TM0316⁽²⁾ to evaluate the Sulfide Stress Cracking resistance on X80 pipe and welds.

There are only limited results about the fatigue behavior of high-strength steel welded joints and, especially, in sour environments. Therefore, the performance of X80 mechanized girth weld was assessed in air and in mild sour environment. Fatigue endurance tests were performed in air at room temperature at loading frequencies of 4-8 Hz and completed by tests at 24°C, pH 5.9, 0.1 psi H₂S partial pressure using a frequency of 0.2 Hz. The in-air fatigue performance of the X80 girth weld was found to be comparable to X65 tested in similar conditions; the results exceeded the BS 7608 class E target curve. The environmental knock down factor (EKDF), which was obtained by comparing the mean of the in-air data with the mean of sour data, is equal to 10.

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Key words: Sulfide Stress Cracking, Corrosion fatigue, Heat Affected Zone, Mildly Sour Service, Carbon/Low Alloy Steel

INTRODUCTION

Pipelines and rigid risers made in conventional X65 grade require large wall thickness to withstand the high loads imposed during installation and under operating conditions in deep and ultra-deepwater field developments. The use of high-strength steels like X80 is an attractive alternative since it improves catenary weight by reducing wall thickness. D. Karunakaran et al.¹ have described the benefits of high strength steels for subsea developments in deep and ultra-deep waters; the main advantages are:

- a reduction of payloads on the floaters
- a reduction of buoyancy requirement for Steel Lazy Wave Risers (SLWR) or Hybrid risers
- more flexibility in the vessel utilization for the pipelaying, allowing the use of smaller vessels and/or reducing the number of vessel transits.

The two main challenges related to the use of high-strength carbon steel risers lie in the suitability for sour service and the fitness for fatigue application. These two challenges were explored by D. Karunakaran et al.¹ on girth welds made on seamless X80 pipes in 323.9 x 25.4 mm. They built a mapping of Sulfide Stress Cracking (SSC) performance of the material, by testing different pH and H₂S partial pressures. The welding solution was demonstrated to be resistant to SSC cracking in moderately sour environment. The fatigue lifetime of the welds was also investigated using full-scale specimens tested in air after reeling simulation and aging at 250°C. The experimental S-N data showed that fatigue performance exceeding the design curve X' of API⁽³⁾ RP 2A WSD 21st edition can be achieved in air with the X80 girth welding procedure they proposed.²

A degradation of the fatigue resistance was observed at high stress cycles with C-Mn steels in sour environment. The extent of the degradation depends on H₂S concentration, pressure, and temperature; Appropriate experimental data are required to determine the impact of the environment on the fatigue lifetime to ensure a proper design of risers and pipelines.³⁻⁶ Yu et al. reviewed the available S-N data obtained on small-scale specimens of C-Mn steels tested in sour environments and conducted a thorough analysis of the fatigue endurance knock-down factors compared with air.⁷ They proposed a conservative knock down factor of 45 indexed to BS 7608 E design curve⁽⁴⁾ for tests in NACE TM 0177 solution B at pH 3.5 and 70 mbar H₂S partial pressure.⁸⁻⁹ Yet, most of the published results of corrosion fatigue tests relate to API X65 welds and there are only limited data about the fatigue performance of X80 girth weld.³

In this context, one of the aims of the present work is to characterize the fatigue performance of a proprietary X80 welds in 323.9 x 25.4 mm in air and in mild sour conditions. It was chosen to perform the corrosion fatigue tests in the same environment as the one used by Ghosh et al.¹⁰ for the testing of girth welded X65 seamless line pipe (10-in. x 35 mm), allowing a comparison of fatigue lifetimes of X80 and X65 welds in an environment representative of some potential future oil and gas field development.

In addition to the endurance fatigue tests, the second objective of this work is to evaluate the sour service performance of the X80 weld joint under static load in fit-for-purpose condition. This sour service performance characterization is supported by detailed hardness measurements at the surface layer of the specimens. As stressed by Yue et al.¹¹, microhardness Vickers measurements using 0.5 kg or 0.1 kg loads allow to detect areas of high hardness that are difficult to identify with HV10 line surveys. Therefore, microhardness mappings were carried out in this study to get a deeper understanding of the relation between the hardness distribution and the SSC performance of X80 weld joint.

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EXPERIMENTAL PROCEDURE

Materials

Tests have been performed on proprietary X80Q seamless pipes in 323.9 x 25.4 mm, which were manufactured using the plug rolling process. After the hot rolling, the seamless pipes were full body quenched and tempered. The chemical composition of the heat is given in Table 1.

Table 1
Steel composition in wt% (balance Fe)

C	Si	Mn	P	S	Nb+V+Ti	Others	Fe	Carbon Equivalent ⁽⁵⁾	
								CE _{IW} ¹³	CE _{pcm} ¹⁴
0.06	0.25	1.5	0.01	0.001	0.08	Mo, Cu, Ni, Al, N	Bal.	0.41	0.18

The tensile properties of the pipe used for this study are given in Table 2. The tests were performed on strip and round specimens taken in longitudinal direction as per ASTM⁽⁶⁾ E8 standard.¹²

Table 2
Tensile results of X80 pipe in as-received condition

Specimen type	Yield strength [MPa]	Tensile Stress [MPa]	Yield ratio	Elongation at break [%]
Strip	607	675	0.90	53
Round specimen (Ø 12.7 mm)	574	643	0.89	29

Girth welding

The girth welding operations were based on the STT / PGMAW process. Surface Tension Transfer (STT) process was used for the welding of the root pass. This is a controlled short-circuit transfer process that allows a good control of the weld root profile owing to its lower heat input used for the deposition of the weld metal. This contributes to minimize the stress concentration at the weld toe. The following weld passes were performed with the Pulsed Gas Metal Arc Welding (PGMAW) process, therefore ensuring good weld fusion together with good mechanical properties and welding productivity.

All welding was performed in the vertical down direction. A 3° J bevel, together with the use of ER70S filler wire for the root pass and an ER80S-G filler wire, with 0.8% Ni content, was used for all subsequent weld passes. A minimum preheat temperature of 125°C was maintained throughout welding. The pipe joints were aligned and assembled to maintain a maximum hi/lo of 0.5 mm. Post weld non-destructive examination inspection was performed by Magnetic Particle Inspection (MPI), Radiographic Tests (RT) and Manual Ultrasonic Tests (MUT) in general accordance with DNV-ST-F101 standard from Det Norske Veritas^{(7), 15}

⁽⁵⁾ CE_{IW}: Carbon equivalent adopted by the International Institute of Welding based on Dearden and O'Neill formula.¹³

Pcm: Carbon equivalent based on Ito-Bessyo formula.¹⁴

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The tests performed on the girth weld consisted in macro- and micro-hardness measurements, SSC tests with four-point bend specimens and small-scale fatigue tests in air and in mild-sour environment. All the tests were carried out on girth weld samples in as-welded condition.

Hardness measurements

Hardness tests using Vickers scale with a load of 10 kg. were done according to ASTM E384 on specimen sampled in the cross section of the weld bead.¹⁶ This hardness specimen was taken at the same position as the four-point bend specimens i.e., at 1 o’ clock. The hardness values were measured in the base metal, the heat affected zone and the weld metal according to DNV-ST-F101.

On completion of the SSC tests, micro-hardness mappings were also performed on the four-point-bend specimens using Vickers indentations with a load of 0.5 kg. The micro-hardness measurements were carried out at the weld root area, using a spacing of 0.25 mm between indents, as shown in figure 1.

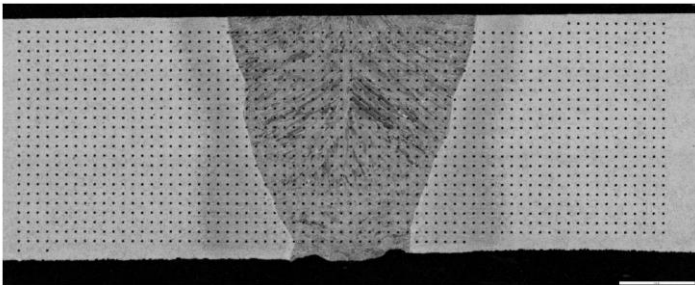


Figure 1: hardness survey of four-point bend specimen – spacing: 250 μm

Fatigue endurance testing

Small scale fatigue endurance tests were carried out in air and in sour environment using dog-bone specimens extracted transverse to the girth weld (full wall thickness) with cap ground flush and weld root left intact. The specimens were prepared with a gage length of 100 mm and a gage width of 50 mm, as shown in Figure 2.

All tests were done at constant stress ratio, $R = 0.1$. Three levels of stress ranges were applied: 103 MPa, 207 MPa and 276 MPa.

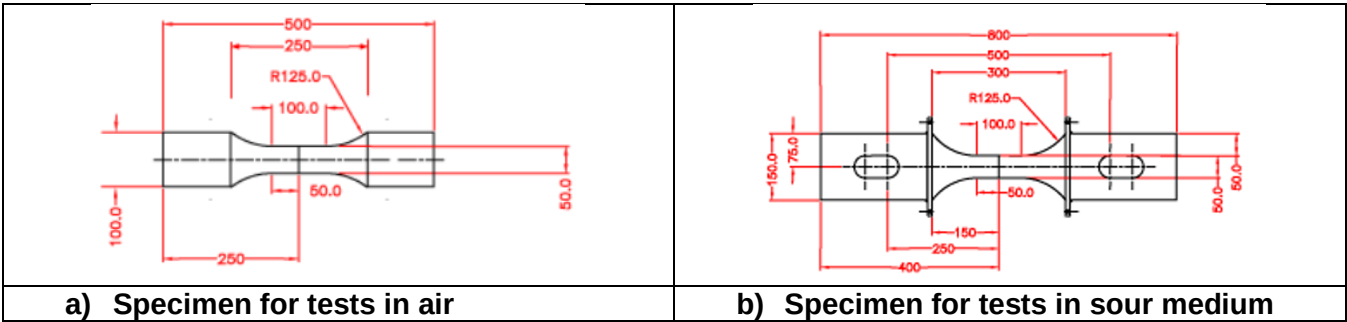


Figure 2: Specimen designs for the fatigue endurance tests in air and in sour environment

Fatigue Endurance testing in air

Fatigue endurance tests were performed under direct axial loading in air and at room temperature using loading frequencies of 4-8 Hz. The specimens were equipped with strain gauges placed at the root side

at 10- and 25-mm distance from the weld toes. The measured strains were extrapolated to estimate the local stress at the weld toes.

Fatigue Endurance testing in mild sour environment

The environmental tests were performed in a sealed Polyvinylidene Fluoride (PVDF) chamber. The environmental conditions used for these tests are given in Table 3. The runout was set at one million cycles.

Fatigue crack growth rate in sour environments depends on the loading frequencies. Conducting sour fatigue tests at frequencies significantly higher than the in-service conditions can lead to non-representative results since it does not properly replicate the interactions between material and environment. Typical riser environmental loading frequencies are in the range 0.1 – 0.2 Hz.¹⁰ In the present study, a frequency of 0.2 Hz was selected for the sour fatigue testing; this allows comparing X80 to X65 results obtained by Ghosh et al.¹⁰ in similar environment.

Except for the area of 75 mm on either side of the weld root, the specimens were coated with a special lacquer prior to testing to limit the contamination of the solution by corrosion product. Strain gauges were installed in the same way as in-air tests to evaluate the local stress at the weld toes. These measurements had to be carried out prior to the sealing of the specimens in the container.

Once sealed in the PVDF chamber, the specimens were pre-soaked in the test solution saturated with the test gas for 24 hours prior to initiate the fatigue cycles.

Table 3
Environmental testing conditions

Solution mg/L						pH	ppH ₂ S (psi)	ppCO ₂ (psi)	ppN ₂ (psi)	P _{total} (psi)	Temp (°C)
[NaCl]	[KCl]	[CH ₃ COONa]	[Na ₂ SO ₄]	[NaHCO ₃]	CaCl ₂ ·2H ₂ O						
12.75	0.15	3.3	0.05	0.72	0.67	5.9	0.1	11.0	3.4	14.5	24±3

Post-test examination

On completion of the fatigue tests, the specimens were immersed in liquid nitrogen and broken open to expose the fracture faces, which examined by light microscopy.

Four-point bend tests

Four-point bend tests were performed to evaluate the SSC resistance of the girth weld in mild sour condition according to NACE TM0316 standard.¹⁷ The tests were done using coupons in 5 x 15 x 115 mm taken from the girth weld at 1 o'clock position.

As displayed in Figure 3, it was chosen to conduct the four-point bend tests in more severe pH and H₂S partial pressure than the fatigue tests for the sake of conservatism. The SSC tests were run for a duration of 720 h at 24°C, pH 5.0 and a partial pressure of H₂S of 2 psi balanced with CO₂ (Region 2).

The testing solution used for the four-point bend tests was a modified NACE TM0177 solution B; sodium bicarbonate was added to adjust the pH.⁹ The four-point bend specimens were loaded at an applied stress of 85% of the SMYS for API X80 material with weld root left intact, which makes the tests more representative compared to machined coupons.

After testing, magnetic particle inspection (MPI), macrographic observation at x10 magnification and micrographic observations were carried out on the tested specimens to assess the presence of cracks.