Girth Welding of API 5L X70 and X80 Sour Service Pipes

The results of this investigation provide a better understanding of welding X70 and X80 pipe developed for sour service

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ABSTRACT

The API 5L X70 and X80 pipes development for sour service application is very recent. Limited information can be found in literature about the girth welding of these materials. This investigation presents the hardness, toughness, tensile, and sour resistance results of welded joints produced on API 5L X70 and X80 pipes developed for sour service. The joints were welded with the gas metal arc welding process for the root pass and flux cored arc welding process for the fill passes. The test methodology included tensile, bending, and nick-break tests as required by the API 1104 standard. The joints were also submitted to Charpy, crack opening displacement (CTOD), hardness, and stress corrosion tests. All joints met the requirements defined by API 1104 for tensile, bending, and nick-break tests. The Charpy tests presented high values of absorbed energy. The weld metal and HAZ of X70 and X80 presented good toughness according to the CTOD results, although one specimen for X80 exhibited low CTOD. All joints met the requirements of the stress corrosion cracking test. Considering all results, the weldability study demonstrated that both X70 and X80 sour service pipes were appropriate for sour service applications. For X80, it is recommended to perform an in-depth analysis of the heat-affected zone (HAZ) toughness before the use of this material. The results presented here can be used for field girth welding of X70 and X80 sour service pipes and provides information leading to a better comprehension of the welding of these recently developed materials.

KEYWORDS

• Sour Service • Pipe • Girth Weld • API 1104 • Crack Tip Opening Displacement (CTOD) • High-Strength Steel

Introduction

Steel plates produced for pipelines are developed to ensure suitable properties for each specific project. Particularly for the onshore part of the pre-salt gas pipelines in Brazil, the pipes are specified with additional requirements for sour service application due to the presence of H₂S in the gas composition. This situation created a big challenge for gas pipeline transportation. The use of conventional API 5L (Ref. 1) grades up to X65 associated with the location class factors could result in heavy wall thickness pipes that are difficult to produce and are not usually used for onshore pipeline construction. The solution found to overcome this challenging scenario was the use of X70 and X80 sour service high-strength steels.

High-strength steels such as X70 and X80 grades have been employed in high-pressure pipelines to avoid the use of thicker pipes, allowing the economic construction of long distance pipelines. However, the production of X70 and X80 for sour service application is a big challenge that requires a more complex production route to ensure resistance against sulfide stress cracking (Refs. 2, 3).

To apply these pipes in onshore pipeline construction, in addition to the challenge of producing a sour service resistance steel, it is necessary to carefully evaluate the girth welding effects on heat-affected zone (HAZ) and weld metal properties.

In high-strength steel welding, a hardness reduction has been observed at the HAZ, also known as HAZ softening (Refs. 4, 5). It is related to the heat input effects on the strengthening mechanism of these steels. Since the sour service steels are produced by accelerated cooling and have lower levels of alloying elements, they may also be susceptible to HAZ softening. Duan, Lazor and Taylor (Ref. 6) commented that the softening effect in the HAZ will potentially cause highly localized deformation, which is undesirable in conditions where strain-based design is applicable. On the other hand, depending on the heat input, the HAZ hard-
ness can increase to values above the limits for sour service application.

Another fact that needs to be studied in the HAZ is the possibility of embrittlement due to either grain coarsening or brittle phase formation. Pepper et al. (Ref. 7) commented that a low toughness can be expected in the coarse-grain HAZ due to grain growth. Furthermore, Terada et al. (Ref. 8) commented that the HAZ toughness can be reduced by the presence of brittle phases, including the formation of martensite-austenite (MA), which according to Babu et al. (Ref. 9) may deteriorate or improve the properties depending on its morphology or concentration of carbon. For weld metal, it is important to evaluate if the high strength levels required do not impair the toughness or increase the hardness above the limits for sour service application.

Although studies on high-strength steel welding are easily found in the literature, the same cannot be said about high-strength steel for sour service, especially for heavy wall thickness pipes. This investigation shows how the girth welding of API 5L X70 and X80 pipes developed for use in sour environments affects weld metal and HAZ properties. The test methodology included tensile, nick-break, side bend, Charpy, crack tip opening displacement (CTOD), hardness, and stress corrosion tests. The results provide technical information to support the application of these materials for onshore gas pipelines from presalt fields.

### Material and Experimental Procedure

#### Pipe Material

The plates for pipe manufacture were produced by a thermomechani-
A controlled process followed by accelerated cooling to produce a fine-grain microstructure. The chemical composition (Table 1) was specially designed to provide a low amount of inclusions and segregation, and thus ensure resistance to stress-corrosion cracking and hydrogen-induced cracking. According to Kalwa (Ref. 2), the steel works have to provide a lean chemistry avoiding alloying elements that tend to segregate, which would give absorbed hydrogen the chance to recombine to molecular H₂.

It is important to use low-C and low-Mn steel. A low-Mn content prevents the formation of MnS inclusions and a low-C content of below 0.05% contributes to a more homogeneous microstructure by lowering the volume fraction of pearlite and reducing the severity of centerline segregation (Ref. 10). The S content has to be reduced to values below 0.001%, and the steel must be Ca treated to control the remaining inclusions.

In addition, central segregation shall be avoided during the casting process, which is also minimized by keeping the lowest possible content of the elements C, Mn, S, and P (Refs. 2, 11). To compensate for the low levels of C and Mn, alloying elements must be added, and an accelerated cooling technique needs to be used. The target is to achieve a refined ferritic or ferritic/bainitic microstructure with high strength and resistance to sulfide stress cracking and hydrogen-induced cracking.

The API 5L X70 and X80 pipes were formed by the UOE process, where the plate is conformed to an U shape followed by an O shape, joined by submerged arc welding, and then cold expanded (E), according to API 5L standard (Ref. 1). The diameter and the wall thickness were 20 1 in. (508 25.4 mm) for X70 and 24 1.25 in. (610 31.8 mm) for X80.

**Welding**

The pipes were cut in rings around 300 mm in length and beveled according to Fig. 1, taken from ASME B31.8 (Ref. 12). The girth welding was done with the pipe fixed in the horizontal position.

The gas metal arc welding (GMAW) process using short circuit transfer was used for the root pass due to its higher productivity and the thicker weld metal that can be deposited with one pass (usually around 4 mm), when compared with processes such as shielded metal arc welding (SMAW) or gas tungsten arc welding (GTAW). For fill and cap passes, the gas-shielded flux cored arc welding (FCAW) process was applied since it also has good productivity.

Consumables with different strength levels were selected according to manufacturer’s recommendation to meet the strength requirements of each pipe grade and also to comply with sour service requirements (Table 2). Procario and Melfi (Ref. 13) commented that for sour service applications, weld metal alloy systems should be carefully selected to provide a balance between toughness and hardness. The chemical composition of the consumables can be seen in Table 3. The values were obtained from the certifi-
cates issued by the manufacturers and correspond to the chemical analysis of the same heat of the consumable used in the tests. For each consumable, the chemical analysis was performed according to the requirements of the applicable AWS standard.

Figure 2 shows the API 5L X70 pipe during welding. The pipe girth welding was done with two welders representing the welding conditions found in onshore pipeline construction. Welding parameters are seen in Table 4. A preheating of 100°C and interpass temperature of 175°C were also applied.

After welding, the coupons were inspected by radiographic examination and ultrasonic tested, and they met the requirements of API 1104 (Ref. 14).

**Mechanical Tests and Metallographic Analysis**

Specimens were taken from the weld coupons to perform metallographic analysis and mechanical tests of tensile, nick break, and bending, required by API 1104 (Ref. 14), and also Charpy, hardness, CTOD, and stress corrosion testing.

<table>
<thead>
<tr>
<th>Process</th>
<th>Grade</th>
<th>Consumable</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Cu</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMAW</td>
<td>X70</td>
<td>ER70S-6</td>
<td>0.140</td>
<td>1.52</td>
<td>0.89</td>
<td>0.016</td>
<td>0.010</td>
<td>0.010</td>
<td>0.016</td>
<td>0.028</td>
<td>0.033</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>X80</td>
<td></td>
<td>0.089</td>
<td>1.44</td>
<td>0.84</td>
<td>0.016</td>
<td>0.014</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>FCAW</td>
<td>X70</td>
<td>E81T1-Ni1C</td>
<td>0.046</td>
<td>1.47</td>
<td>0.41</td>
<td>0.010</td>
<td>0.013</td>
<td>0.820</td>
<td>0.030</td>
<td>0.020</td>
<td>—</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>X80</td>
<td>E101T1-G</td>
<td>0.050</td>
<td>1.57</td>
<td>0.38</td>
<td>0.010</td>
<td>0.020</td>
<td>0.900</td>
<td>0.040</td>
<td>0.170</td>
<td>—</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Samples for metallographic analysis were etched with nital 2%, and the images were taken with magnification of 500× by optical microscopy.

The test methods and samples for tensile, nick break, and bending tests of the girth welds were done according to API 1104 (Ref. 14) requirements.

A Vickers hardness test was performed with a load of 10 kgf. The specimen, removed from the 6 o’clock position, was prepared according to Fig. 3 extracted from ISO 15156-2 (Ref. 15) that defines the hardness requirements for sour service.

Charpy impact test specimens were sampled at 2 mm from the inner surface (close to the root pass) and at 2 mm from the outside surface (close to the cap pass) of the pipe for both weld metal and HAZ. The specimens were removed from both one upper and one bottom pipe quadrant. Three full-size specimens of 10 mm × 55 mm were tested according to ASTM A370 (Ref. 16) for each position. The test was carried out at 0°C, which is below the minimum design temperature for onshore pipelines. Figure 4, based on DNV-OS-F101 (Ref. 17), shows the notch positions for the girth weld Charpy test.

The stress corrosion test of three specimens was performed according to ISO 7539-2 (Ref. 18) standard using the four-point loading method — Fig. 5. During the test, a stress level corresponding to 80% of the actual yield strength of the pipe was applied. The stressed samples were exposed to the test solution B of NACE TM 0284 standard (Ref. 19) for 30 days with continuous bubbling of H2S. This solution was chosen because its severity is closer to that recommended by ISO 15156-2 (Ref. 15) to test an operational condition similar to the presalt gas characteristics. The girth weld root was placed in the tensioned area of the specimen and was not machined to test the real weld profile found in circumferential weld roots.

For CTOD tests, single-edge, notched bend specimens were used according to BS 7448 (Ref. 20). The weld metal test was conducted on a through thickness specimen of rectangular sections (Bx2B) with crack plane orientation correspondent to NP, where N means normal to weld direction and P means crack propagation parallel to weld direction, in accordance with BS 7448 (Ref. 20). The HAZ test was conducted on surface-notched specimens of square sections (BxB) with crack plane orientation corresponding to NQ, where N means normal to weld direction and Q means crack propagation in the weld thickness direction according to BS 7448 (Ref. 20), to place the fatigue precrack at the grain growth region of the HAZ — Fig. 6.

Nine specimens were tested for both the weld metal and HAZ, three from the 12 o’clock position, three from the 6 o’clock position, and three from the 3 o’clock position. The test temperature was –10°C for X70 and 0°C for X80. In fact, the test temperature depends on the minimum temperature of the environment where the pipe will be applied. During the X80 CTOD tests, the minimum temperature had been set to 0°C, later on, it was decided to adopt a more conservative condition for the X70 pipe, and the test temperature was reset to –10°C.

### Table 4 — Process Parameters

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Pass</th>
<th>Number of Passes</th>
<th>Polarity</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Speed (mm/s)</th>
<th>Heat Input (kJ/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X70</td>
<td>Root</td>
<td>1</td>
<td>CC +</td>
<td>15–16</td>
<td>140–190</td>
<td>1.6–2.1</td>
<td>0.9–1.8</td>
</tr>
<tr>
<td></td>
<td>Fill</td>
<td>22</td>
<td>CC +</td>
<td>20–23</td>
<td>180–220</td>
<td>1.8–4.6</td>
<td>0.7–2.3</td>
</tr>
<tr>
<td></td>
<td>Cap</td>
<td>5</td>
<td>CC +</td>
<td>21–23</td>
<td>180–200</td>
<td>3.0–5.5</td>
<td>0.8–1.0</td>
</tr>
<tr>
<td>X80</td>
<td>Root</td>
<td>1</td>
<td>CC +</td>
<td>15–17</td>
<td>120–140</td>
<td>1.6–2.1</td>
<td>0.8–1.5</td>
</tr>
<tr>
<td></td>
<td>Fill</td>
<td>25</td>
<td>CC +</td>
<td>21–23</td>
<td>190–220</td>
<td>2.1–5.5</td>
<td>0.9–2.1</td>
</tr>
<tr>
<td></td>
<td>Cap</td>
<td>5</td>
<td>CC +</td>
<td>21–23</td>
<td>190–210</td>
<td>3.3–4.7</td>
<td>0.9–1.2</td>
</tr>
</tbody>
</table>

### Table 5 — Stress Corrosion Cracking Testing Results

<table>
<thead>
<tr>
<th>Pipe Grade</th>
<th>pH before H2S Saturation / pH at End of Test</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>X70</td>
<td>8.14/5.25</td>
<td>No cracks</td>
</tr>
<tr>
<td>X80</td>
<td>8.17/5.23</td>
<td>No cracks</td>
</tr>
</tbody>
</table>

Fig. 10 — HAZ CTOD.

Fig. 11 — Weld metal CTOD.
Results and Discussion

The weld metal microstructure of X70 and X80 can be seen in Figs. 7 and 8, respectively. The X70 microstructure presented acicular ferrite, grain boundary ferrite, and polygonal ferrite, while the X80 presented a higher amount of acicular ferrite and also some polygonal ferrite.

The results of the weld tensile test for each quadrant are shown in Fig. 9. The horizontal dashed line expresses the minimum acceptable values of 570 MPa for X70 and 625 MPa for X80.

Eight side bending specimens for each joint were tested. No one specimen presented a crack or other discontinuity greater than 3 mm, so that all specimens of both materials met the requirements for the bending test. For the nick-break test, four specimens from each joint were tested, one for each quadrant, and all of them met the API 1104 (Ref. 14) acceptance criteria.

Considering the results of tensile, bending, and nick-break tests, the welding procedure was considered qualified according to API 1104 (Ref. 14). However, to meet the specific requirements for presalt gas pipelines and perform a deep evaluation, other tests such as Charpy, CTOD, hardness, and stress corrosion were necessary.

Charpy and CTOD tests were carried out to verify the weld metal and HAZ toughness. Figure 10 presents the CTOD results of the HAZ and Fig. 11 the CTOD of the weld metal. Only the CTOD valid specimens were plotted so that less than three results may appear for some positions. The horizontal dashed line represents the minimum acceptable value of 0.15 mm recommended by Hopkins and Denys (Ref. 21) to allow the use of a fitness-for-purpose criteria. This minimum value is required to ensure that plastic collapse equations can predict defect failure stresses. This provides more possibilities from the engineering point of view to deal with situations where specific analysis is necessary, such as defects found during in-service inspection and to avoid unnecessary repairs (Ref. 21).

Figure 10 shows that one X80 specimen presented a CTOD value below 0.15 mm for the HAZ. Barnes (Ref. 22) commented that local brittle zones exist within the HAZ, especially within those regions of the grain-coarsened HAZ, reheated into the intercritical regime by subsequent weld passes. These brittle zones are formed due to the formation of MA constituent.

According to Barnes (Ref. 23), the scatter observed in the test data can be explained by the inhomogeneity of the microstructure and by the fact that the local brittle zones are small so that the crack tip can be, or not, at these regions.

Barnes (Ref. 23) suggested that the thermal simulation techniques can reduce the inherent variability and allow
close matching of the thermal conditions and microstructure at various locations in a multipass HAZ. This, in turn, allows easier and more accurate testing and examination.

To perform a more accurate evaluation, a study based on the API RP Z2 (Ref. 24) standard could be used to evaluate the HAZ toughness with different heat inputs. Moreover, a microstructural evaluation would help to check if the presence of MA in the HAZ is contributing to a toughness reduction.

The weld metal CTOD values presented at Fig. 11 are very close to the minimum recommended value of 0.15 mm. Generally, the alloying elements added to meet high strength levels increases the challenge to meet high toughness requirements for weld metal. Felber (Ref. 25) observed that to meet the high strength requirements it is necessary to supply a weld metal with additions of nickel and molybdenum. These elements are included in the chemical composition of E81T1-Ni1C and E101T1-G used for X70 and X80 welding, respectively. According to Procario and Melfi (Ref. 13), although molybdenum is used to increase toughness in the as-welded condition by promoting the formation of acicular ferrite, it can reduce the toughness when reheated because these reheated regions do not retain their fine-grained acicular ferrite microstructure.

For X70 grade, some results were below the minimum. One alternative to improve weld metal toughness for X70 is changing the shielding gas composition from the mixture of 80% argon and 20% CO2 to 100% CO2. Alloying elements used for deoxidization such as Mn and Si can remain in the weld metal when the gas mixture of Ar and CO2 is used and therefore reduce toughness (Ref. 26). The use of a shielding gas of 100% CO2 reduces the amount of Mn and Si and also increases the oxygen level in the weld metal, promoting inclusion formation that can increase the volume fraction of acicular ferrite and improve toughness. In order to test the effect of shielding gas, another X70 welded joint was produced with a shielding gas of 100% CO2. Figure 12 shows that the CTOD results were improved, and Fig. 13 shows that a large amount of acicular ferrite was obtained, when compared with Fig. 7.

Charpy results are shown in Figs. 14 and 15 for the weld metal and the HAZ, respectively. As the onshore pipeline welding standard API 1104 (Ref. 14) does not specify Charpy requirements for a girth weld, the value of 45 J specified by DNV-OS-F101 (Ref. 17) for X80 will be used as a reference. This value is represented by a horizontal dashed line.

For both X70 and X80, the absorbed energy values were above the minimum required. The HAZ presented higher absorbed energy values than the weld metal.

The hardness results for X70 and X80 are shown in Fig. 16. The horizontal dashed line represents the limit of 250 HV defined by ISO 15156-2 (Ref. 15).

From Fig. 16, it can be noted that all hardness impressions do not exceed the limit of 250 HV10 defined by ISO 15156-2 (Ref. 15).

Figure 16 also shows an HAZ softening, which is more pronounced for X80. According to Denys and Lefevre (Ref. 4), the susceptibility to HAZ softening increases with the reduction of alloying elements and with increasing heat input. Due to the low amount of alloying elements in sour service steels, hardness reduction was expected in this region. According to Duan, Lazor, and Taylor (Ref. 6), it can be critical for submerged arc welding where the softening effect in the HAZ will cause highly localized deformation, which is undesirable where strain-based design is applicable.

Duan, Lazor, and Taylor (Ref. 6) also commented that a narrow HAZ is not expected to have a high level of local deformation due to the high lateral constraint from the adjacent parts of the weld metal and the unaffected pipe body. As the materials evaluated in this study were designed for use in a stress-based design, and the heat input is lower than that from the submerged arc welding process, it can be concluded that the HAZ softening found is not critical for X70 and X80 sour service pipe welding.

The stress corrosion cracking test for both X70 and X80 girth welds concluded that the weld joints are suitable for sour service. After 30 days immersed in a test solution, no cracks were found. Table 5 summarizes the test results.

As mentioned by Procario and Melfi (Ref. 13) for sour service application, the weld metal chemical composition must be carefully selected to provide a good balance between toughness and hardness. Furthermore, for X70 and X80 grades, the welded joint must also meet the high strength levels required. The tests results obtained in this study show that the girth welding of high-strength steel sour service pipes is feasible.

**Conclusions**

The weldability study using the
GMAW process for the root pass and the FCAW process for fill passes were evaluated for both X70 and X80 sour service pipes. According to API 1104 requirements, the welding procedures can be considered approved.

The X80 HAZ presented low toughness according to one specimen evaluated by CTOD tests. In fact, the CTOD test is not required to meet the workmanship criteria of API 1104. However, a low toughness can restrict a fitness- for-purpose analysis to avoid unnecessary repairs of defects found during in-service inspection or even the pipeline construction. It is recommended to perform an in-depth evaluation to identify the reasons behind this low CTOD value presented.

The X70 weld metal presented low toughness when welded with the mixture of 80% Ar and 20% CO2. However, shielding gas of 100% CO2 increased the CTOD results to values above 0.15 mm. According to the literature, this improvement can be attributed to two main factors: the reduction of deoxidizing elements, such as Mn and Si in the weld metal, and the increased volume fraction of acicular ferrite due to inclusions formation caused by the increased oxygen level in the weld metal.

The Charpy impact test presented high values of absorbed energy and all specimens met the requirements.

The stress corrosion cracking test demonstrated that the welded joints are appropriate for sour service application. Both the welding parameters and consumables applied showed to be suitable for X70 and X80 girth welding for sour service.

Considering all results presented, the weldability study demonstrated that both X70 and X80 sour service pipes are appropriate for sour service applications.

Acknowledgments

This paper presented the results of a weldability study applied in X70 and X80 pipes developed for sour service. The results obtained can be used for field girth welding of these materials and provides information that leads to a better comprehension of the welding of these recently developed materials.

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References