

## EVALUATION OF OVERMATCHING, TOUGHNESS AND SOUR SERVICE PROPERTIES OF X65 GIRTH WELDING\*

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### **Abstract**

The present work is a part of a comprehensive program that aims to evaluate the girth welding procedures for heavy wall API 5L X65 pipes produced for sour service applications. This article describes the results of toughness, strength and sour resistance of girth welds produced with different welding consumables. The methodology applied included girth welds production with GTAW process for root pass using ER70S-6 consumable and FCAW process for filling passes using E71T-1CJ and E91T1-GM-H4 consumables. Mechanical tests of Charpy, CTOD, tensile, hardness and stress corrosion cracking were also performed. The E71T-1CJ resulted in a girth weld with tensile and yield strength around 7% lower than the pipe. However, according to the papers analyzed at this study, a value up to 10% of undermatching could be acceptable. The CTOD and Charpy tests showed good toughness and weld metal embrittlement was not observed. The hardness and the stress corrosion cracking tests demonstrated that the consumable ER70S-6 is suitable for sour service. All properties evaluated met the requirements specified by the onshore pipeline standards, showing that the consumables ER70S-6, E71T-1CJ and E91T1-GM-H4 are suitable for the welding of heavy wall X65 pipe with sour service and toughness requirements. If an overmatching is required, the E91T1-GM-H4 shall be used to assure a strength overmatching and prevent plastic strain concentration at the weld metal. The results provided by this paper can be used for consumable selection and for welding procedure qualification of pipelines construction when heavy wall API 5L X65 are used for sour gas transportation.

**Keywords:** API 5L X65; Sour service; Overmatch; Toughness.

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## 1 INTRODUCTION

In an onshore pipeline design, the pipe grade is basically defined by the design pressure and the outside diameter of the pipe. For large diameter and high pressure pipelines, high strength steels are usually selected in order to avoid heavy wall thickness pipes. However, as the pipe grade increases, the difficult to meet the sour service requirements also increases so that it is necessary to change the steel chemical composition and process parameters in order to provide resistance against the stress corrosion cracking and hydrogen induced cracking. The API 5L [1] X65 grade have a long history of application in sour service projects while the X70 and X80 sour grades are still a challenge for steel and pipe producers.

During the design stage of the Rota 2 pre-salt gas pipeline, the API 5L X65 was the higher grade available for sour service application, leading to a pipe wall thickness of 1.452 inches (36.88 mm). In order to produce a proper girth weld during the pipeline construction, it is necessary select suitable welding consumables and defines the requirements that they need to meet. The high strength consumables could produce a microstructure with high hardness, low ductility and a low resistance to sulfide stress cracking. On the other hand, the use of a lower strength consumable can result in a welded joint with undermatching.

The purpose of this study is to evaluate the properties of the weld metal produced with different consumables selected for the pipeline girth welding. The methodology applied included welding of test coupons and mechanical tests such as hardness, stress corrosion cracking, tensile and toughness tests. The analysis was focused on the joint properties of toughness, strength mismatching and resistance to stress corrosion cracking. The results provided by this paper can be used for consumable selection and for welding procedure qualification of pipelines construction when heavy wall API 5L X65 are used for sour gas transportation.

## 2 MATERIAL AND METHODS

### 2.1 Pipe Material

To carry out this study, small rings of around 400 mm were extracted from API 5L X65 pipes produced by SAW UOE process with sour service requirements. The diameter and the wall thickness of the rings were 24 inches (610 mm) and 1.452 inches (36.88 mm) respectively and they were beveled according to ASME B31.8 [2]. The plates used to make the pipes were produced by the thermo-mechanical controlled rolling process (TMCP) followed by accelerated cooling in order to produce a fine grain microstructure that provides high strength, toughness and good weldability. The alloy design, casting and rolling process parameters were establish in order to produce a 1.452 inches (36.88 mm) plate suitable for sour service. Table 1 shows the chemical composition of the pipes.

**Table 1.** Chemical composition

Pipe	C	Mn	Si	Nb	V	Ti	Cr	Cu	Mo
A	0.04	1.45	0.31	0.045	0.001	0.014	0.036	0.232	0.019
B	0.04	1.42	0.30	0.044	0.001	0.014	0.046	0.204	0.027
Pipe	Ca	Al	N	P	S	Ni	B	Carbon Equivalent	
								IIW	Pcm
A	0.0012	0.035	0.0056	0.011	0.001	0.265	0.0003	0.33	0.15
B	0.0013	0.032	0.0046	0.010	0.001	0.264	0.0003	0.33	0.14

## 2.2 Consumables for Welding

The welding of test coupons was carried out with a combination of two different welding processes. The GTAW (Gas Tungsten Arc Welding) process was chosen for the root and hot passes and the FCAW (Flux Cored Arc Welding) process for the filling and cap passes. For filling and cap passes, two consumables of different strength levels were used.

According to Procario and Melfi [3] the weld metal alloy system for sour service application should be carefully selected to provide a balance between toughness and hardness. For root and hot passes, the GTAW consumable used was the AWS A5.18 [4] ER 70S-6, and for filling and cap passes the FCAW consumables used were the AWS A5.20 [5] E71T-1CJ and also the AWS A5.29 [6] E91T1-GM-H4 that have higher strength in order to provide an overmatching. The chemical composition of the consumables can be seen in Table 2. Table 3 shows the consumables mechanical properties.

**Table 2.** Consumables chemical composition

Consumable	C	Mn	Si	P	S	Ni	Cr	Mo	Cu	V
ER 70S-6	0.079	1.66	0.96	0.013	0.008	0.010	0.030	0.005	0.058	0.002
E71T-1CJ	0.072	1.20	0.45	0.019	0.010	0.008	0.024	--	--	--
E91T1-GM-H4	0.059	1.37	0.36	0.012	0.010	2.090	--	--	--	--

**Table 3.** Consumables mechanical properties

Consumable	Typical mechanical properties			Mechanical properties specified by AWS			
	AWS Specification and classification	YS* (MPa)	TS* (MPa)	Absorbed energy / temperature	YS* (MPa)	TS* (MPa)	Absorbed energy / temperature
A5.18	ER 70S-6	525	595	70J/-30°C	400	480	27J/-30°C
A5.20	E71T-1CJ	565	605	130J/-40°C	390	490-670	27J/-40°C
A5.29	E91T1-GM-H4	640	705	95J/-18°C and 66J/-50°C	540	620-760	27J/-40°C

\* YS – Yield strength. TS – Tensile strength.

## 2.3 Welding of Test Joints

The pipe girth welding was carried out representing the welding conditions found in an onshore pipeline construction. The pipe axis was fixed with an inclination of 15 degrees and the welding direction was vertical up for both processes. A preheating of 100°C and interpass temperature of 175°C were applied. Figure 1 shows the GTAW and FCAW welding.

The root and hot passes were done with ER70S-6 and the filling and cap passes were done with E71T-1CJ for pipe A and E91T1-GM-H4 for pipe B. The shielding gas composition was 100% Ar for ER70S-6, 100% CO<sub>2</sub> for E71T-1CJ and 80%Ar/20%CO<sub>2</sub> for E91T1-GM-H4. Table 4 shows the welding parameters.



Figure 1. Welding of test joints.

Table 4. Welding parameters

Pipe	Process	Consumable	Pass	Voltage (V)	Current (A)	Speed (mm/s)	Heat input (kJ/mm)
A	GTAW	ER70S-6	Root	9-12	100-130	1.40-1.48	0.85-0.91
			Hot	10-14	160-176	1.41-1.57	1.15-1.61
	FCAW	E71T-1CJ	Filling+cap	22-27	135-190	1.5-3.79	1.11-2.63
B	GTAW	ER70S-6	Root	11.5	100	0.56	2.04
			Hot	12.2	160	1.16	1.68
	FCAW	E91T1-GM-H4	Filling+cap	22-22.5	163-179	2.02-5.18	0.76-1.87

## 2.4 Mechanical Tests

Specimens were sampled from the test coupons for tensile, hardness, Charpy and CTOD tests. The stress corrosion cracking test was carried out only for the test joint of pipe A. As just the weld root is really tested during the stress corrosion cracking test and the test joint of pipe B was welded with the same consumable of pipe A for root pass, it was not necessary undergo the test joint of pipe B to stress corrosion cracking test.

Tensile tests were carried out on pipe body in order to compare the longitudinal tensile properties of the pipe with the all weld tensile results. Three round test pieces were tested for all weld tensile test and five for pipe body. The test was performed according to ASTM A370 [7]. Figure 2 shows the specimen dimensions.

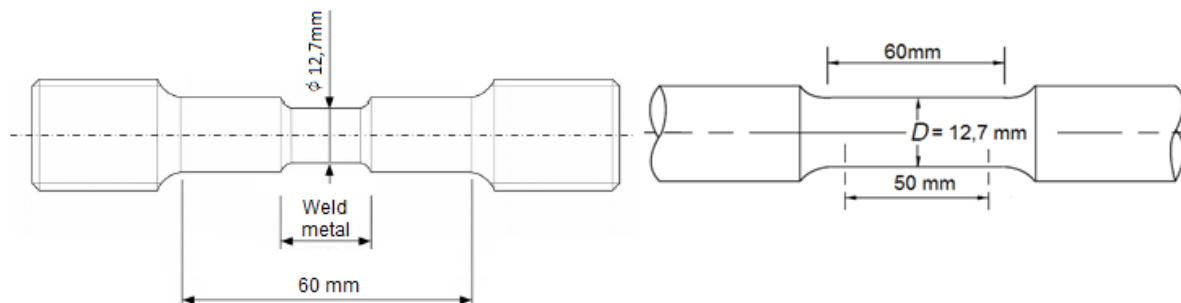


Figure 2. Tensile test specimen dimensions.

For pipe A, 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. For pipe B, specimens were

sampled only for weld metal at the middle of wall thickness. The specimens were removed from both upper and bottom pipe generatrix. For each location, three specimens were tested according to ASTM A370 [7]. Three full size specimens of 10x10x55 mm were tested for each position and the test temperature was 0 °C. The Vickers hardness specimens were prepared according to Figure 3 extracted from ISO 15156-2 [8]. The specimen was sampled from the pipe bottom and tested with a load of 10 kgf.

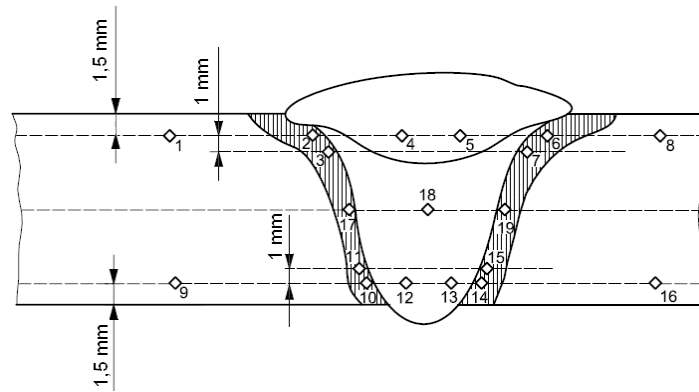


Figure 3. Hardness profile [8].

In order to use the benefits of a fitness for service criteria, API 1104 [9] requires the crack tip opening displacement (CTOD) test that provides a better assessment of fracture toughness [10]. The weld metal test was conducted on through thickness single edge notched bend specimen of rectangular sections (Bx2B) with orientation correspondent to NP in accordance with BS 7448 [11]. The test temperature was 0°C. For both pipe A and Pipe B, nine specimens were tested, three from 12 o'clock position, three from 6 o'clock position and three from 3 o'clock position.

The stress corrosion cracking test was performed according to ISO 7539-2 [12] using the four point loading method (Figure 4) in order to check whether the consumable used for the weld root is suitable for sour service. During the test, a stress level correspondent to 72% of the specified minimum yield strength of the pipe was applied. Three stressed samples were exposed to the test solution B of NACE TM 0284 [13] standard for 30 days with continuous bubbling of H<sub>2</sub>S. This solution was chosen because its severity is closer to that recommended by ISO 15156-2 [8] to test an operational condition similar to the pre-salt gas characteristics. The weld root was not machined in order to test the real weld profile found in girth welds.

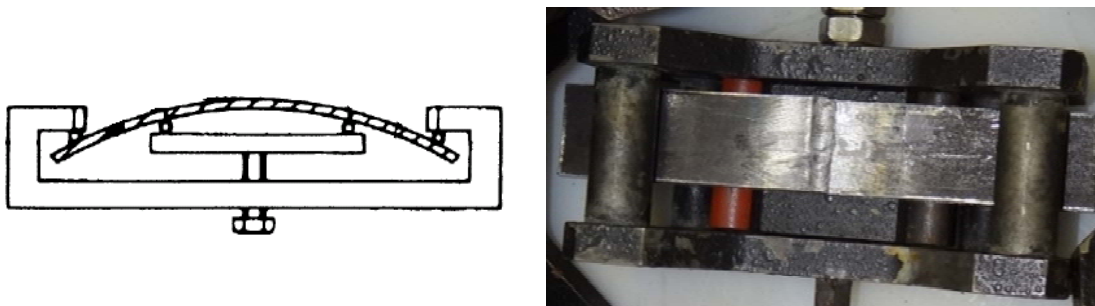


Figure 4. Four point loading.

### 3 RESULTS AND DISCUSSION

Figure 5 shows that the yield and tensile strength of the consumables E71T-1CJ and E91T1-GM-H4 are higher than the minimum required by AWS A5.20 [5] and AWS



A5.29 [6] specifications respectively. The consumables also presented values above the minimum required by the API 5L for the X65 pipe grade.

The E71T-1CJ results show that the use of a consumable with tensile properties higher than the minimum specified for the pipe, does not guarantee a welded joint with overmatching. It can be noted that the E71T-1CJ yield and tensile strength are below the values obtained from the pipe. On the other hand, the consumable E91T1-GM-H4 showed values above the actual yield and tensile strength of the pipe. It can be said that the pipe welded with E71T-1CJ presented undermatching while the pipe welded with E91T1-GM-H4 presented overmatching.

The E71T-1CJ average value of undermatching was 7% for yield strength and 5% for tensile strength. The E91T1-GM-H4 presented an overmatching average value of 45% and 42% for yield and tensile strength respectively.

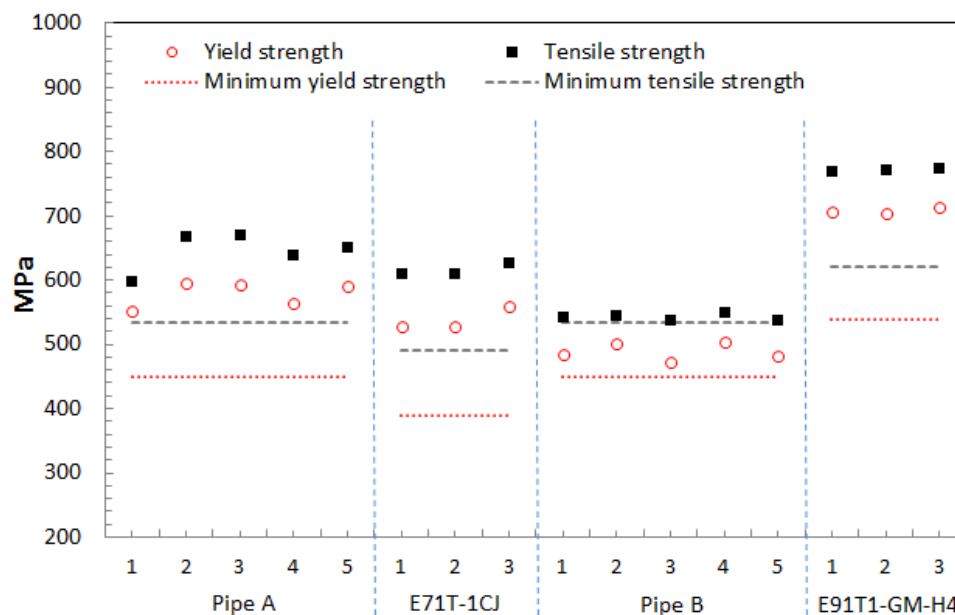


Figure 5. Yield and tensile strength of pipe and consumables.

The undermatching presented by the E71T-1CJ does not mean that it cannot be acceptable for pipeline welding. Wang [14] comments that the weld strength needed depends on the expected stress or strain imposed on the welds and other relevant weld parameters, such as the flaw size and high-low misalignment. On the other hand, undermatching may result in excessive localized strain in the weld and cause imperfection growth [10]. According to Wang [14], depending on the specific loading condition in the pipe longitudinal direction, the girth welds can be sound and safe even with some degree of undermatching.

An alternative to ensure overmatching would be specify a high strength weld metal in order to overcome the maximum strength allowed by the pipe specification. However, having weld strength greater than the pipe strength could result in lower toughness and ductility which could lead to an overall inferior weld quality [14]. In fact, a good balance between toughness and strength shall be pursued.

Wang [14] recommends that the maximum undermatching shall be limited to 10%. This value was obtained after analyzing different combinations of wall thickness, misalignment, flaw size, stress level, CTOD results and applied strain. Dexter [15] concluded that if there are no significant defects in the weld, a 10% undermatch of weld metal strength should be tolerable for the case of monotonic loading. In

contrast, a 10% undermatched weld may not be suitable in the case of cyclic plastic loading such as from pipe reeling.

As the E71T-1CJ presented undermatching below 10% and no plastic strain is expected by the pre-salt onshore pipelines, it can be assumed that the E71T-1CJ can be acceptable from the strength point of view.

The E91T1-GM-H4 overmatches the base material in around 45%. It may be a concern from the point of view of toughness. In general, when the consumable strength increases, the toughness tends to decrease.

Figure 6 shows the absorbed energy values from Charpy tests. The dashed black line represents the Charpy test machine capacity which means that the results that match this line are in fact higher than those presented. As the onshore pipeline welding standard API 1104 [9] does not specify Charpy test for girth weld, the value of 38J specified by DNV-OS-F101 [16] will be used as reference.

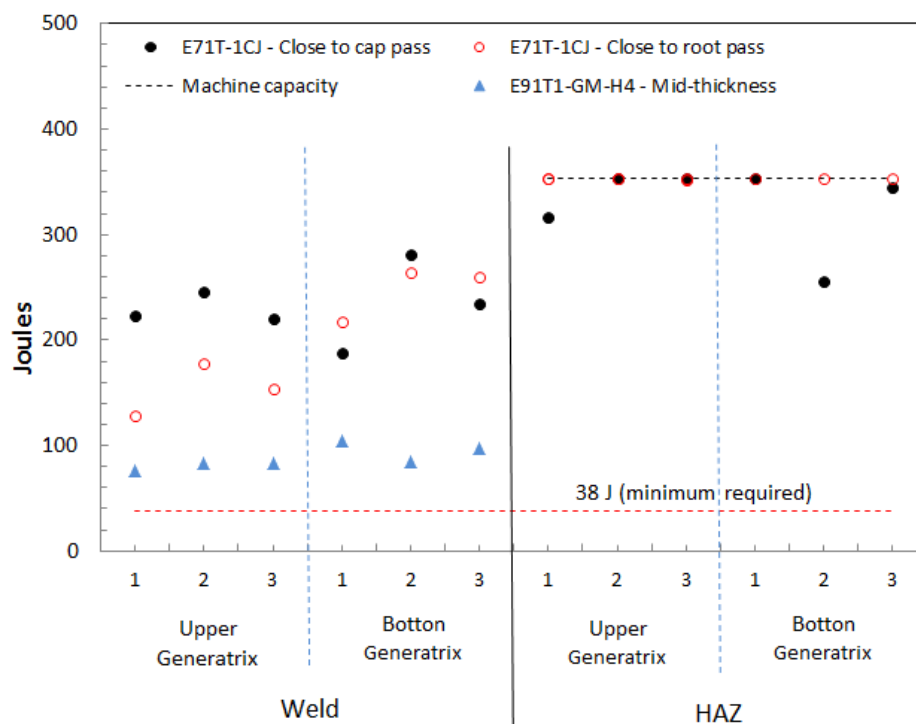


Figure 6. Charpy absorbed energy results.

Both consumables presented absorbed energy values higher than the 38 Joules specified by DNV-OS-F101 [16]. As it was expected, the E91T1-GM-H4 absorbed energy is lower than the E71T-1CJ, since the increase in tensile and yield strength tends to reduce the toughness. It was also observed that the HAZ presents higher absorbed energy than the weld metal.

The CTOD test shown in Figure 7 demonstrated that both consumables presented high toughness. All CTOD values of both consumables were above 0.15 mm. This value is recommended by Hopkins and Denys [17] in order to allow the use of a fitness for purpose criteria. This provides more possibilities to deal with situations where specific analysis is necessary such as dispense from stress relieving heat treatment, defects found during in-service inspection and to avoid unnecessary repairs.

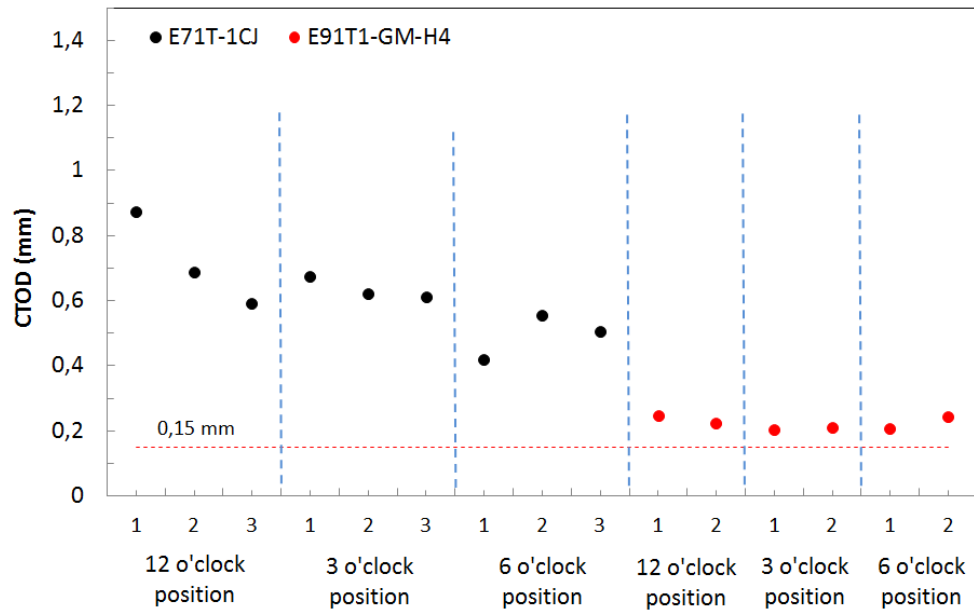


Figure 7. CTOD results.

Hardness test is one of tests required to assure that the welded joint is suitable for sour service applications. According to ISO 15156-2 [8], the hardness should be below 250 HV at the weld root and 275 HV in the regions not exposed to the fluid. Figure 8 shows that the E91T1-GM-H4 presented hardness values above the E71T-1CJ and also above the hardness measurements number 12 and 13 that represents the weld metal ER 70S-6 used for root pass. The E91T1-GM-H4 has higher tensile strength values and also higher hardness. However, all results are below the limit of 250 HV, represented by a dashed red line.

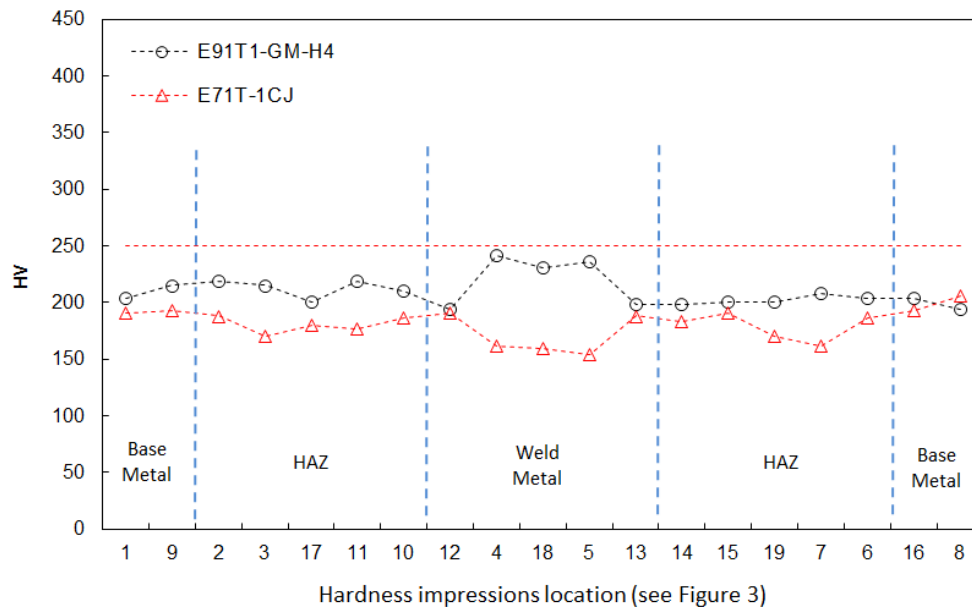
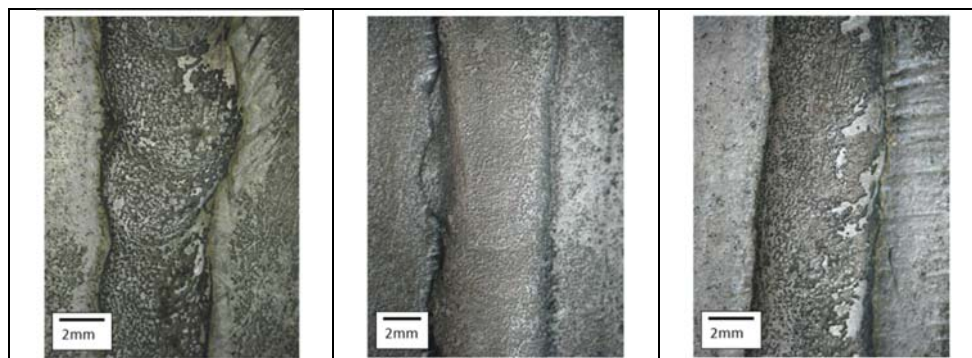


Figure 8. Hardness test results.

The stress corrosion cracking test was done to assure that the consumable ER70S-6 used for root pass is suitable for sour service. After 30 days immersed in a test solution, no cracks were found. Figure 9 shows the weld root of three different



specimens. The absence of cracks proved that the ER70S-6 is suitable for sour service.



**Figure 9.** Weld root after stress corrosion cracking test.

All properties evaluated met the requirements specified by the onshore pipeline standards, showing that the consumables ER70S-6, E71T-1CJ and E91T1-GM-H4 are suitable for the welding of a heavy wall X65 pipe with sour service and toughness requirements. However, the consumable E71T-1CJ does not overmatch the pipe base metal. It does not mean that an undermatching welded joint is not suitable for onshore pipeline. According to Wang [14], the weld strength mismatch requirement is only one of the necessary components to achieve satisfactory weld performance. Moreover, the undermatching presented is below 10% for both yield and tensile strength. According to some references [14, 15] a value of 10% of undermatching can be accepted since the welded joint is not submitted to high strain.

#### 4 CONCLUSION

Both E71T-1CJ and E91T1-GM-H4 consumables presented yield and tensile strength higher than the minimum required for the X65 base material. However, the E71T-1CJ did not match the actual pipe strength leading to an undermatching of around 7% at the girth weld. According to the papers analyzed at this study, a value up to 10% of undermatching could be acceptable. On the other hand, the E91T1-GM-H4 overmatches the pipe base material at around 45%.

The E91T1-GM-H4 consumable presented lower toughness than the E71T-1CJ. Despite this difference, the values presented exceeded the Charpy and CTOD desired values. It was not observed weld metal embrittlement.

The hardness of E91T1-GM-H4 was around 70HV higher than the E71T-1CJ. Nevertheless, hardness values for both consumables were below the maximum of 250HV required for sour service applications. Furthermore, the stress corrosion cracking test demonstrated that the consumable ER70S-6 used for root pass is suitable for sour service. All specimens were approved and no cracks were found.

All properties met the onshore pipeline girth welding requirements, showing that the consumables ER70S-6, E71T-1CJ and E91T1-GM-H4 are suitable for heavy wall X65 pipe girth welding with sour service and toughness requirements. If the pipeline design demands overmatching weld due to events that results in plastic strain, the E91T1-GM-H4 shall be preferred, otherwise, the E71T-1CJ can be used.

The results provided by this paper can be used for consumable selection and for welding procedure qualification of pipelines construction when heavy wall API 5L X65 are used for sour gas transportation.

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