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Welding and Heat Treatment of Heavy Wall API 5L X65 Sour Service Pipes

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Abstract

In the design of the onshore part of the export gas pipeline from pre-salt, due to the high design pressure, it will be necessary to apply pipes with wall thickness of 1.452 inches, that is much higher than the thicknesses traditionally used in onshore pipelines, which rarely exceeds 1 inch. According to the design code ASME B31.8 and the Brazilian standard NBR 12712, when the wall thickness exceeds 1.25 inches, it is necessary to perform a stress relieving heat treatment after welding. The mandatory requirement of the standard raises some concerns, such as the difficulty of carrying out this treatment in field conditions, the heating effect in mechanical properties of pipe body and the stresses imposed by thermal expansion, particularly in the tie-in welds where the restrictions are significant. In the gas to be transported by these pipes, there is also the presence of H_2S which can result in sulfide stress cracking. To avoid this, it is necessary to use pipes and welding procedures suitable for sour service, including sulfide stress cracking test and hardness test. Due to the particularities of this project, it was decided to conduct a comprehensive welding study that serves as the basis for the use of this material in the field. In this study, the girth weld and pipe body were evaluated in the heat treated and without heat treatment conditions. The methodology of analysis included tensile, nick-break, side bend, Charpy, CTOD, hardness, HIC and SSC tests. Additionally, the CTOD results were compared with the results from a fracture mechanics study that was done considering the residual stress not relieved because the absence of heat treatment. The results demonstrated that the heat treatment decreases the yield and tensile strength of the API 5L X65 sour service pipe. On the other hand, all requirements were fulfilled in the as welded condition.

1. Introduction

The current needs to export gas from the pre-salt fields have created a new challenging scenario for the pipeline construction techniques and materials specifications. For the onshore part of the pipeline, due to the high design pressure and H_2S presence, it was necessary to specify pipes with wall thickness higher than the ones traditionally used and with good resistance to sulfide stress corrosion cracking and hydrogen induced cracking.

For steel and pipe manufacturers it is not an easy task to produce thicker pipes and also meet sour service requirements. A good process control is required to prevent segregation and ensure the formation of a sour service resistant microstructure. Few manufacturers in the world are able to produce this type of pipe.

Another point that has to be considered is that, according to the design code ASME B31.8 [1] and the Brazilian standard NBR 12712 [2], when the wall thickness exceeds 1.25 inches, it is necessary to perform a stress relief heat treatment after welding. The mandatory requirement of the standard raises some concerns, such as the difficulty of carrying out this treatment in field conditions, the heating effect in mechanical properties of pipe body and the stresses imposed by thermal expansion, particularly in the tie-in welds where the restrictions are significant. Besides, there is not much information available about onshore pipeline construction using stress relief heat treatment and the chemistry of the sour service pipe is not suitable for this process. In order to face this scenario, Petrobras decided to conduct a comprehensive welding and heat treatment study that serves as the basis for the use of this material in the field. This paper shows the results obtained from two different welding processes with and without performing heat treatment.

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2. Material and Experimental Procedure

2.1. Pipe Material

The X65 sour service pipes used in this study were produced by the SAW UOE process according to API 5L specification [3]. The diameter and the wall thickness were 24 inches and 1.452 inches respectively. The chemical composition can be seen in Table 1 and it results in a carbon equivalent IIW of 0.33% and Pcm of 0.14%.

Table 1. Chemical composition.

C	Mn	Si	Nb	V	Ti	Cr	Cu	Mo	Ca	Al	N	P	S	Ni	B
0.04	1.42	0.30	0.044	0.001	0.014	0.046	0.204	0.027	0.0013	0.032	0.0046	0.01	0.001	0.264	0.0003

The plates used to make the pipes were produced by the well-known thermo mechanical controlled rolling process (TMCP) followed by accelerated cooling that produces a fine grain microstructure that provides high strength, toughness and good weldability. It is important to mention that the alloy design and the rolling process parameters were establish to produce a 1.452 inches plate suitable for sour service. They were not designed to keep the X65 properties after post weld heat treatment.

2.2. Welding

The pipe was cut in small rings of around 400 mm each to produce the welded coupons. The girth welding was done representing a real field situation with the tube fixed in the horizontal position. Figure 1 shows the type of bevel used in the preparation of pipe ends.

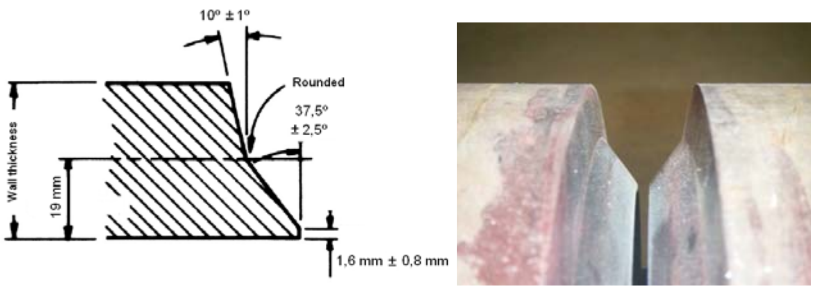


Figure 1. Bevel geometry.

With the intention to assure good quality and avoid repairs in the root pass, a welding procedure using TIG process was established for root and hot passes. For filling and cap passes a semi-automatic flux cored arc welding process with shielding gas protection (FCAW-G) was used.

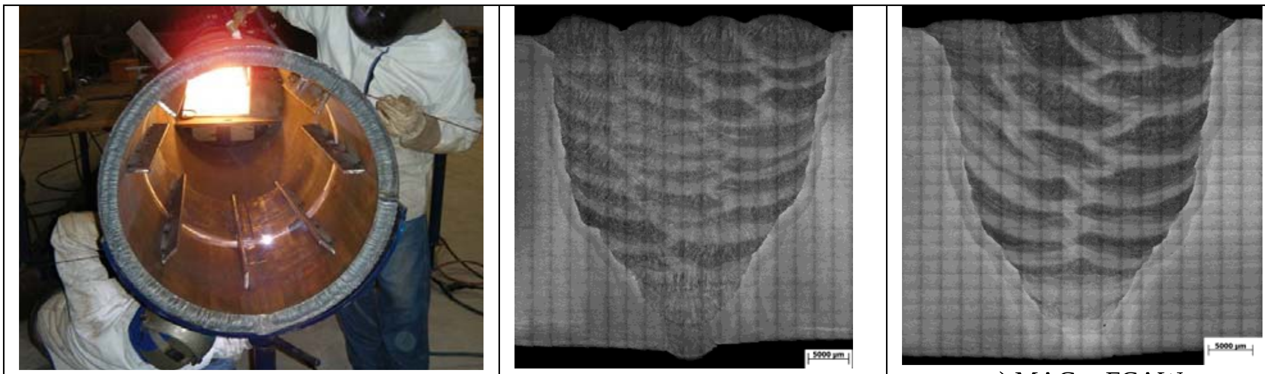
In order to maximize productivity in welding, a second procedure was also tested using the semi-automatic MAG CSC process (controlled short circuit) for the root pass and a semi-automatic flux cored arc welding process with shielding gas protection (FCAW-G) for the filling and cap passes.

Six coupons were welded (3 for each welding procedure) and then immediately tested and six other coupons were welded (3 for each welding procedure) and heat treated. Two rings, one in as received condition and another one after heat treatment, were also tested in order to evaluate the pipe properties. Table 2 summarizes the number of coupons and rings used in the study.

Table 2. Number of rings and coupons tested.

Procedure Identification		Welding Process	Number of Coupons (Welds)	Number of Rings
A	As welded	**TIG** (root pass) + **FCAW**-G (filling passes)	3	6
B	Heat treated		3	6
C	As welded	**MAG** CCC (root pass) + **FCAW-G** (filling passes)	3	6
D	Heat treated		3	6
E	Original pipe	Pipe body	-	1
F	Heat treated pipe		-	1
Total			12	26

Twelve welded coupons and two rings were used to evaluate the welding procedures and the effect of the heat treatment. The welding was performed with two welders at the same time (Figure 2a). The weld profiles for both procedures are shown in Figure 2b) and c) and the welding data can be seen in Table 3.



a) Welding activity. b) TIG + FCAW. c) MAG + FCAW.

Figure 2. Welding activity.

Table 3. Welding data.

Process	TIG: root and hot passes FCAW-G: filling and cap passes	MAG: root pass FCAW-G: filling and cap passes
Welding direction	TIG: vertical up FCAW: vertical down	MAG: vertical down FCAW: vertical up
Shielding gas	Root: 100% Ar (10 l/min) Filling: 100% CO_2 (15 l/min)	Root: 75%Ar / 25%CO_2 (15 l/min) Filling: 100% CO_2 (15 l/min)
Preheat and interpass	100 ºC / 175 ºC	
Comsumables	TIG: AWS A 5.18, ER 70S-6 FCAW: AWS A5.20, E71T-1CJ	MAG: AWS A 5.18, ER 70S-6 FCAW: AWS A5.20, E71T-1CJ
Amperage (A)	TIG: 122 – 128 FCAW: 155 – 180	MAG: 90 – 103 FCAW: 163 – 194
Voltage (V)	TIG: 9.58 – 10.18 FCAW: 24.34 – 26.25	MAG: 16.10 – 16.48 FCAW: 24.39 – 24.74
Polarity	TIG: CC^- / FCAW: CC^+	MAG: CC^+ / FCAW: CC^+
Wire speed (inch/min)	TIG: Not applicable FCAW: 284.21	MAG: 175 FCAW: 287.36
Welding speed (cm/min)	TIG: 6.85 FCAW: 14.20	MAG: 11.05 FCAW: 14.55
Heat Input (kJ/cm)	TIG: 10.63 – 11.86 FCAW: 16.55 – 20.82	MAG: 7.91 a 9.37 FCAW: 17.07 a 20.70

After welding, all coupons were inspected and approved by radiographic examination according to API 1104 [4] requirements.

2.3. Stress Relieving Heat Treatment

After girth welding, six coupons, three welded with TIG + FCAW and three welded with MAG+FCAW, were heat treated. Additionally, one ring of pipe body, including the SAW longitudinal weld, was also heat treated to evaluate its influence in the pipe properties.

Figure 3 shows the pipe preparation for stress relieving heat treatment. The heating method applied was electric resistance.

Figure 3. Heat treatment.

The stress relieving heat treatment was performed according to the following parameters:

- Soaking temperature: 595 ºC ± 15 ºC.
- Soaking time: 90 minutes.
- Heating rate: 55 ºC/h to 150 ºC/h.
- Cooling rate: 55 ºC/h to 185 ºC/h.

Figure 4 shows the heat treatment arrangement.

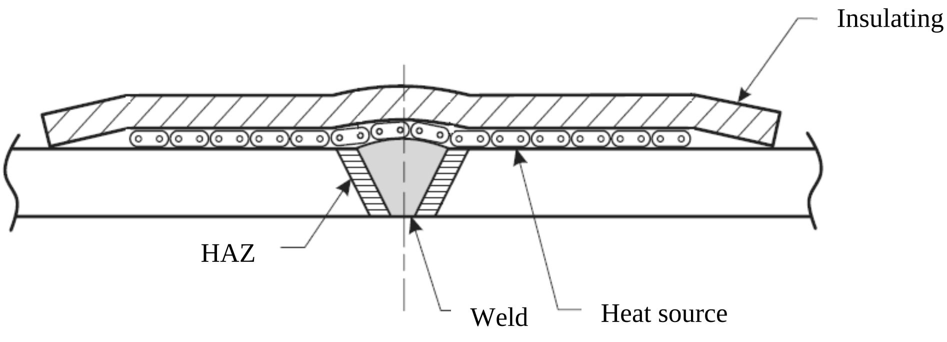


Figure 4. Electric resistance heating.

2.4. Metalographic and Mechanical Tests

Specimens were sampled from the welded coupons to perform the mechanical tests required by API 1104 (tensile, nick-break and bending) and also Charpy, hardness, metallography and stress corrosion test. Additionally, CTOD testes (Crack Tip Opening Displacement) were done to compare the results with the critical value defined by the fracture mechanics study.

One heat treated pipe ring including the SAW longitudinal seam was also evaluated with mechanical tests and compared with another ring representing the pipe original condition, without heat treatment. In this case, tensile, Charpy, hardness, metallography, SSC (Sulfide Stress Cracking) and HIC (Hydrogen Induced Cracking) tests were performed.

All tests were done in the as welded and heat treated conditions in the girth weld as well as pipe body and SAW longitudinal weld.

The test methods and samples for tensile, nick-break and bending tests of the girth welds were done according the API 1104 requirements. Figure 5 and Figure 6 shows the specimens geometry and dimensions.

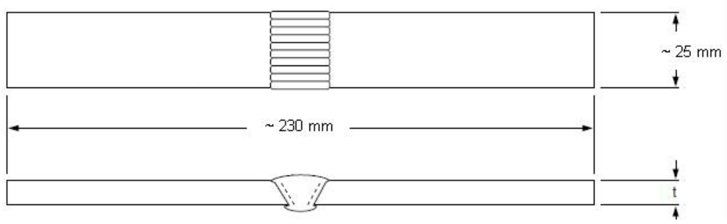
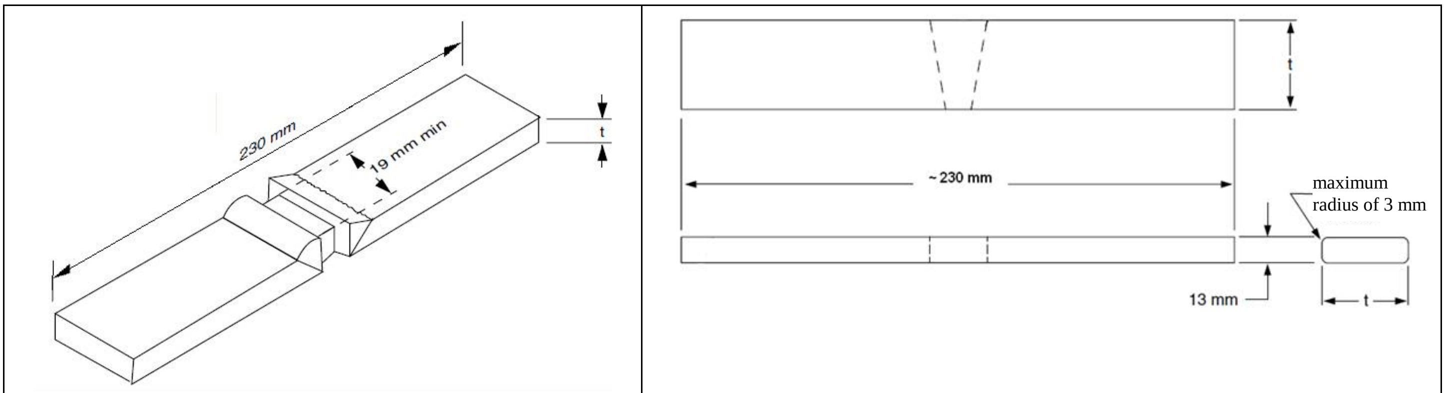


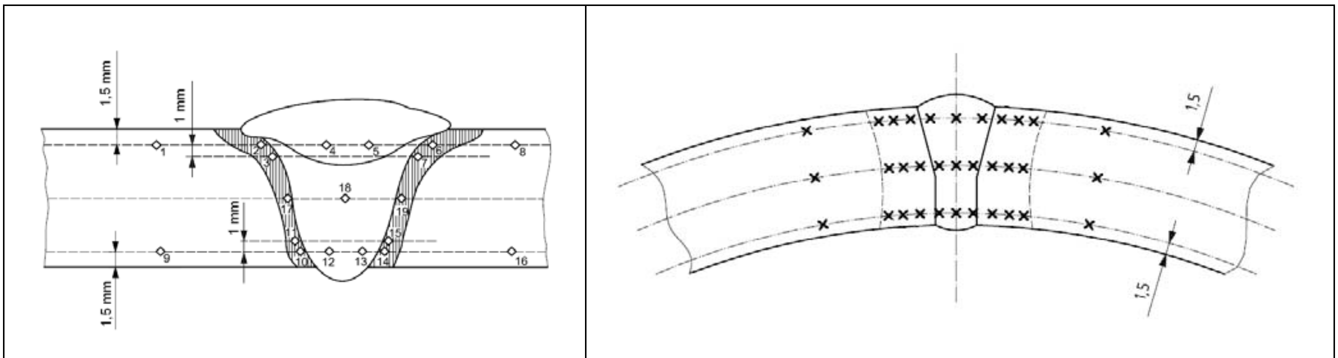
Figure 5. Tensile specimen dimensions.



a) Nick-break specimen dimensions. b) Bending specimen dimensions.

Figure 6. Nick-break and bending specimens.

The Vickers hardness specimens were prepared according to ISO 15156-2 [5] (Figure 7a) for girth weld and according to API 5L for the SAW longitudinal weld (Figure 7b).



a) Girth weld. b) SAW longitudinal weld.

Figure 7. Hardness profile.

Charpy impact test specimens of the girth weld were sampled at 2 mm from the inner surface (close to the root pass) and 2 mm from the outside surface (close to the cap pass) of the pipe for both weld metal and HAZ. Figure 8 a) shows the notches position for girth weld Charpy test.

For pipe body and longitudinal weld seam, the specimen orientation and the HAZ notch location are shown in Figure 8 b).

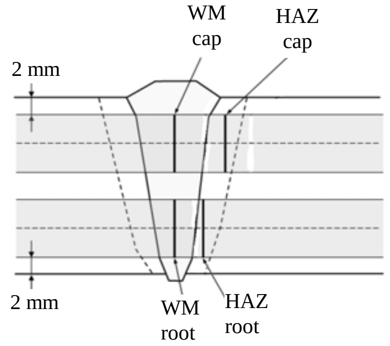
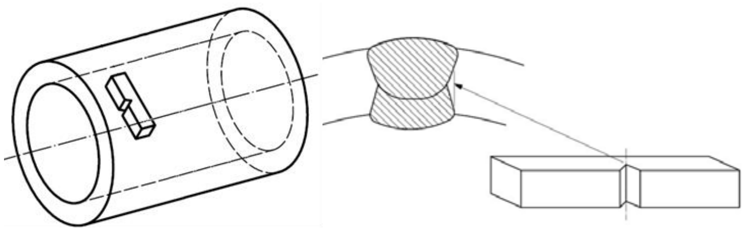
	
a) Girth weld notch position.	b) Pipe body and longitudinal weld seam.

Figure 8. Specimen orientation and notches position.

The specimen preparation and test method were performed according to ASTM A370 [6]. Three full size specimens of 10 x 10 x 55 mm were tested for each position and the test temperature was 0 ºC.

Tensile tests of pipe body and longitudinal seam were done according to API 5L requirements. For each ring, with and without heat treatment, two round bar specimens were sampled from the pipe body and two strip specimens were sampled from the SAW longitudinal weld. Figure 9 shows the tensile specimen dimensions.

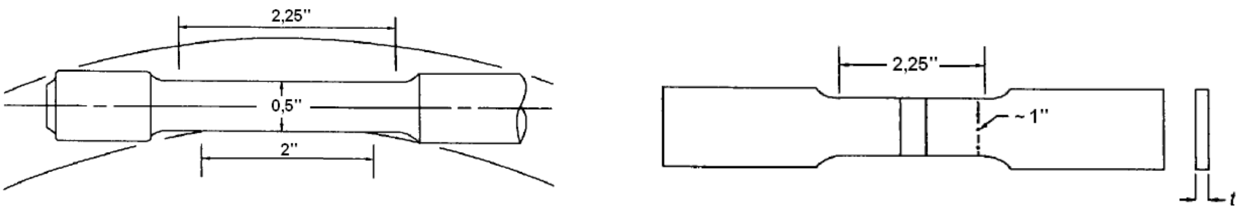


Figure 9. Tensile specimens.

The HIC test was performed in the pipe body for both conditions, with and without heat treatment. The test methodology and specimens preparation were done in accordance with NACE TM 0284 [7] standard and the test solution defined for the test was solution B of NACE TM 0177 [8] standard. Three specimens were removed according to the orientation shown in Figure 10. During the test, all samples were exposed to the test solution for 96 hours with continuous bubbling of H_2S.

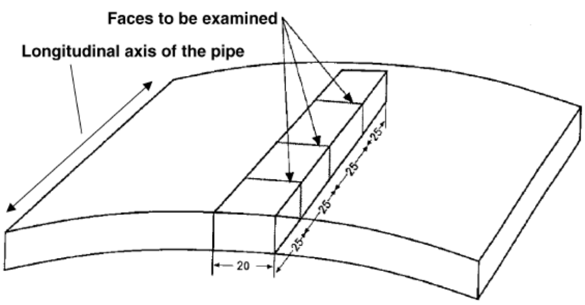


Figure 10. Orientation of test specimens.

The sulfide stress corrosion cracking test was performed in the girth weld, base metal and SAW weld seam according to the ISO 7539-2 [9] standard using the four point loading method (Figure 11). Three specimens were tested for each region (base metal, SAW weld and girth weld). During the test, a stress level correspondent to 72% of the specified minimum yield strength of the pipe was applied. The stressed samples were exposed to the test solution B of NACE TM 0284 standard for 30 days with continuous bubbling of H_2S. The girth weld root was preserved during the test as can be seen in Figure 12.

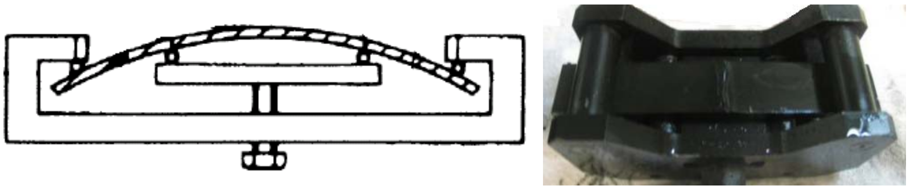


Figure 11. Four point loading.

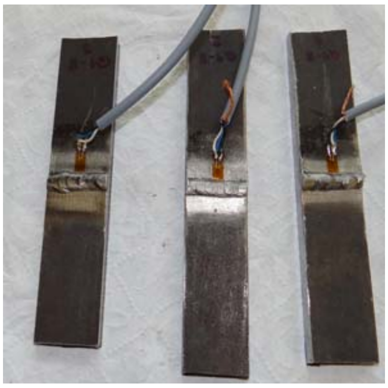
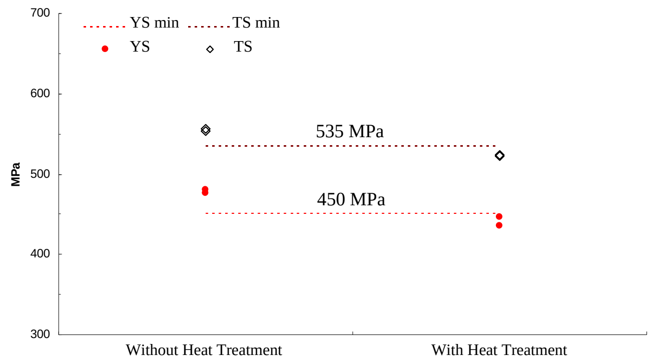


Figure 12. Girth weld specimens.

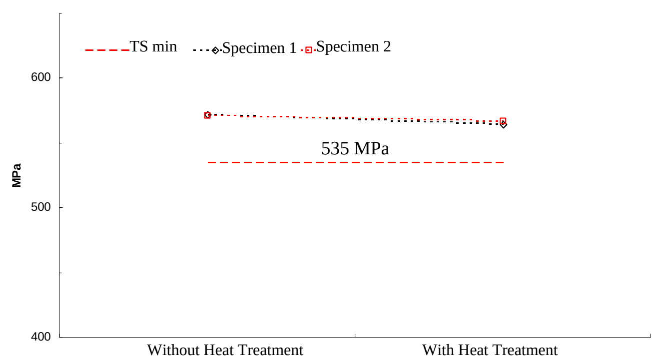
For CTOD tests, SEB specimens were used according to BS 7448 [10] and oriented so that its length is parallel to the pipe axis and its width is in the circumferential direction. The weld metal test was conducted on through thickness specimen of rectangular sections (Bx2B) with orientation correspondent to NP in the notation of BS 7448. The HAZ test was conducted on surface notched specimens of square sections (BxB) with orientation corresponding to NQ in the notation of BS 7448. Nine fracture toughness tests, three from 6 o'clock position, three from 12 o'clock position and three from 3 o' clock position were carried out in both weld metal and HAZ.

3. Results and Discussion

The stress relieving heat treatment affected the tensile properties of API 5L X65 pipe manufactured to meet sour service requirements. The decrease in yield and tensile strength for specimens sampled from pipe body (Figure 13a), and tensile strength for specimens sampled from girth weld (Figure 14) confirms that the heat treatment is not indicated for this type of material. For girth weld tests, the specimen fracture occurred at base metal (Figure 15), showing that the weld strength was not strongly affected by heat treatment and that the pipe base material is susceptible to stress relieving heat treatment. Figure 13b) shows that the tensile strength of the SAW longitudinal weld was affected by heat treatment but, in this case, it is above the minimum value required by API 5L.

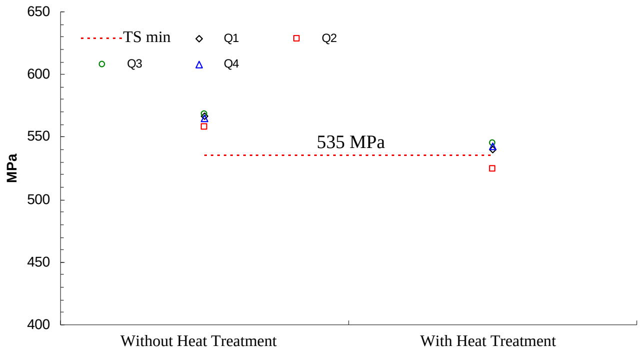


a) Pipe body yield and tensile strength.

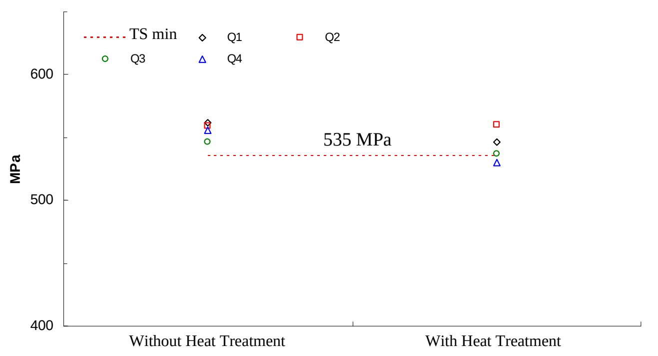


b) SAW weld seam tensile strength.

Figure 13. Yield and tensile strength results from pipe body and SAW weld seam.



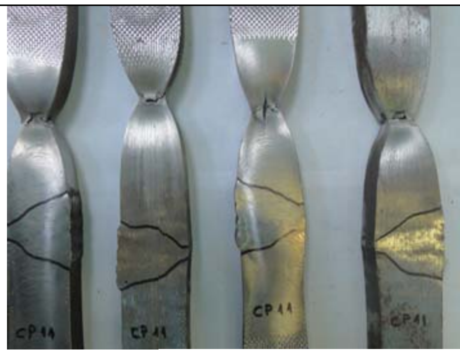
a) Tensile strength (TIG + FCAW).



b) Tensile strength (MAG + FCAW).

Figure 14. Tensile strength results of girth welds.

a) TIG + FCAW



b) MAG + FCAW

Figure 15. Tensile specimens of girth welds.

Groeneveld [11] analyzing the effect of stress relieving heat treatment in a X70, 20 inches x 0.5 inch pipe, manufactured by the HFW process, observed an increase in yield strength after the pipe has been subjected to a heat treatment of 45 minutes at 594 °C. The time difference between Groeneveld's treatment and the treatment applied in the pipe of this study can be explained by the wall thickness difference between these two pipes. The ASME B31.8 states the time of the treatment according to the wall thickness of the pipe, specifying the value of 1 hour per inch of wall thickness.

One factor that may help to understand the difference between the increase in yield strength obtained by Groeneveld [11] in contrast with the decrease of yield strength observed in this study may be the difference in chemical composition between these two steels. Table 4 shows the chemical compositions found in both cases.

Table 4. Comparison between chemical composition (wt %).

Pipe	C	Mn	Si	Nb	V	Ti	Cr	Cu	Mo	Ca	Al	N	P	S	Ni	B
X65 1.452"	0,04	1,42	0,30	0,044	0,001	0,014	0,046	0,204	0,027	0,0013	0,032	0,0046	0,01	0,001	0,264	0,0003
X70 0.5" [11]	0,038	1,48	0,21	0,047	0,081	0,017	--	0,008	--	--	0,036	0,0028	0,007	0,001	--	--

The main alloying element that could explain the increase in yield strength occurred in the study done by Groeneveld [11] is the Vanadium. Yong et al [12] showed that during the cooling of the steel in the rolling process, the V carbides start to form at the temperature of 719 °C, so that around this temperature, most of the V may still be in solid solution in the austenitic matrix. As the final rooling temperature is around 720 °C, it may be possible that the cooling rate was high enough to keep part of the V in solid solution. Meireles [13] comments that when a steel containing vanadium in solid solution is subjected to tempering (which is the same case of the stress relieving heat treatment), a refined and dispersed carbonitrides precipitation is generated, resulting in an increase of the yield strength.

Meireles [13] also observed an increase in yield strength after a heat treatment at 400 °C for one hour in a X80 pipe containing V, manufactured by controlled rolling without accelerated cooling.

Muthmann [14] explains that the V begins to form carbonitrides in the temperature range between 450 ºC and 500 ºC and reach the peaks of precipitation between 550 ºC and 650 ºC. As the treatment described by Groeneveld [11] was carried out at a temperature of 594 °C in a steel containing V, it can be assumed that V was responsible for the increase in yield strength after the heat treatment.

The absence of V in the steel of this study may explain why the yield strength did not increase, but does not explain why the yield was reduced by heat treatment. One reason may be the loss of work hardening due to the heating.

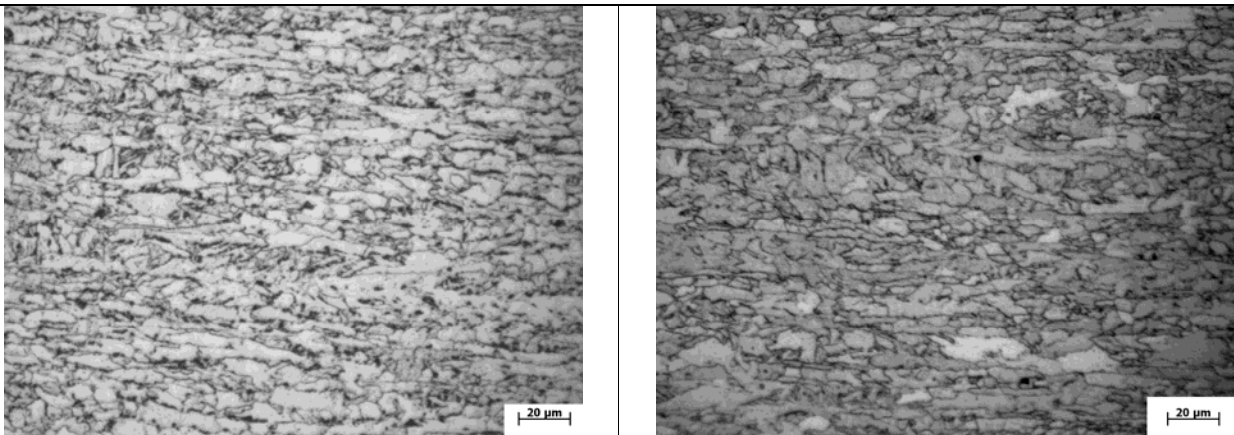
During the pipe production by the UOE process, the pipe is cold expanded, that increases the yield strength by work hardening mechanism, which consists in increasing the dislocation density. With the heating of the heat treatment, the dislocation density decreases and the yield strength is reduced. It is important to mention that the pipe studied by Groeneveld [11] that had the yield strength increased after treatment, contain V in its chemical composition and was produced by the HFW process that does not use cold expansion.

Another case that is closer to the X65 of 1.452 inches evaluated in this study was also studied by Groeneveld [15], using X70 and X80 pipes made from plates. In this case, all pipes that were cold expanded had the yield strength decreased, or kept close to the original value, after stress relieving heat treatment, even those containing V. On the other hand, the only one pipe that had the yield and tensile strength increased, was a pipe containing V produced without cold expansion. Another point that may also be mentioned is that the pipes that had the yield strength decreased had very low carbon content (0.02% to 0.07%) whereas those that had the yield strength increased after heat treatment had higher carbon content (0.12%). Carbon is one of the elements responsible for the phenomenon of strain aging, which tends to increase the yield strength through its diffusion into dislocations regions.

Groeneveld [15] concluded that pipes manufactured from plates produced by controlled rolling processes with accelerated cooling, can have the yield and tensile strength reduced around 10 to 14% by the stress relieving heat treatment.

It is possible to conclude from the literature [11, 12, 13, 14 and 15] that the cold expansion and the presence of vanadium are important factors for pipes that are heat treated for stress relief, where V contributes to increase the yield strength and cold expansion for reduction. Furthermore, the carbon content is another factor that may have a strong influence. As the X65 evaluated in this study have low carbon content, is not alloyed with vanadium and is cold expanded, the expected result is the reduction of yield and tensile strength as noted.

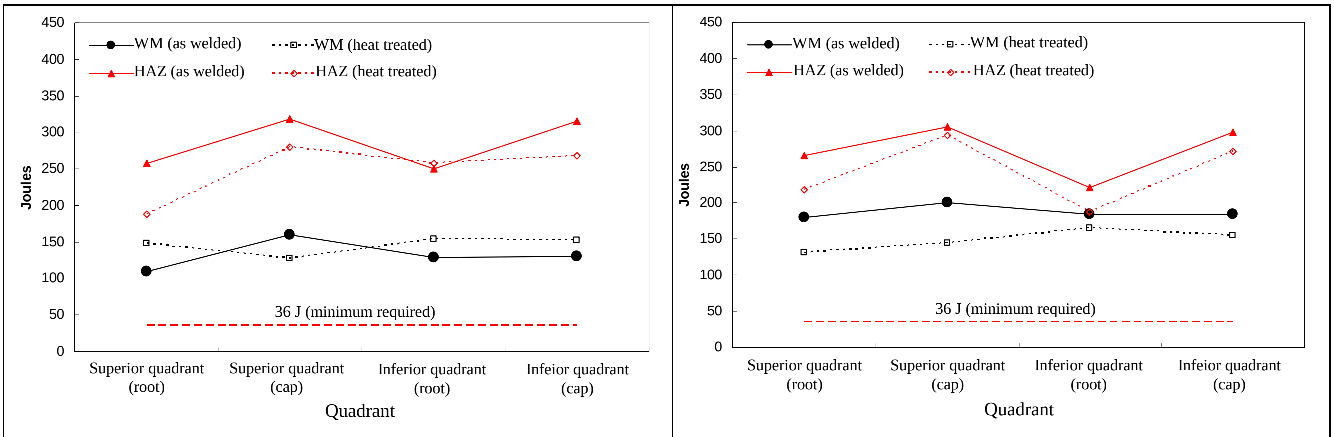
The hypothesis that the yield strength is reduced by grain growth was discarded in this study because the heat treatment temperature is around 600 ºC and the ferrite to austenite transformation begins at Ac1 temperature that is around 700 ºC. If there was not phase transformation, the grain size remains the same as can be seen in Figure 16.



a) Without heat treatment. b) Heat treated.

Figure 16. Microstructure before and after heat treatment.

With the exception of tensile properties, all other properties met the requirements specified in both conditions, with and without heat treatment. The hardness and Charpy tests did not show differences for girth weld in both conditions (Figure 17). Only the Charpy test of SAW longitudinal weld showed a reduction in the impact energy values after heat treatment, but still remaining above the minimum required value (Figure 18). No significant improvement in mechanical properties due heat treatment was observed.



a) TIG + FCAW. b) MAG + FCAW.

Figure 17. Charpy impact test results of girth weld.

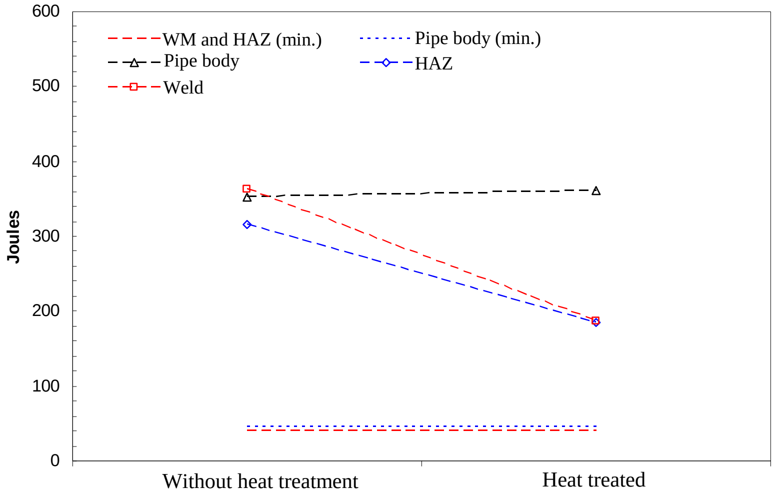


Figure 18. Pipe body and SAW longitudinal weld Charpy results.

Eight side bending specimens for each joint were tested, two in each quadrant. No one specimen presented crack or other discontinuity greater than 3 mm, so that all specimens of all girth welds were approved in the bending test.

In the nick-break test, four specimens for each joint were tested, one for each quadrant, and all of them were approved according to API 1104 acceptance criteria.

In some cases, the heat treatment may be employed as a solution to reduce the hardness and make the material suitable for H_2S service. In the case of this study, the hardness values were below the limit of 250 HV and there was no difference with and without heat treatment (Figure 19 and Figure 20). Moreover, in the HIC and SSC tests, cracks were not detected (Figure 21), confirming the suitability of this material for sour service with no need to perform a heat treatment.

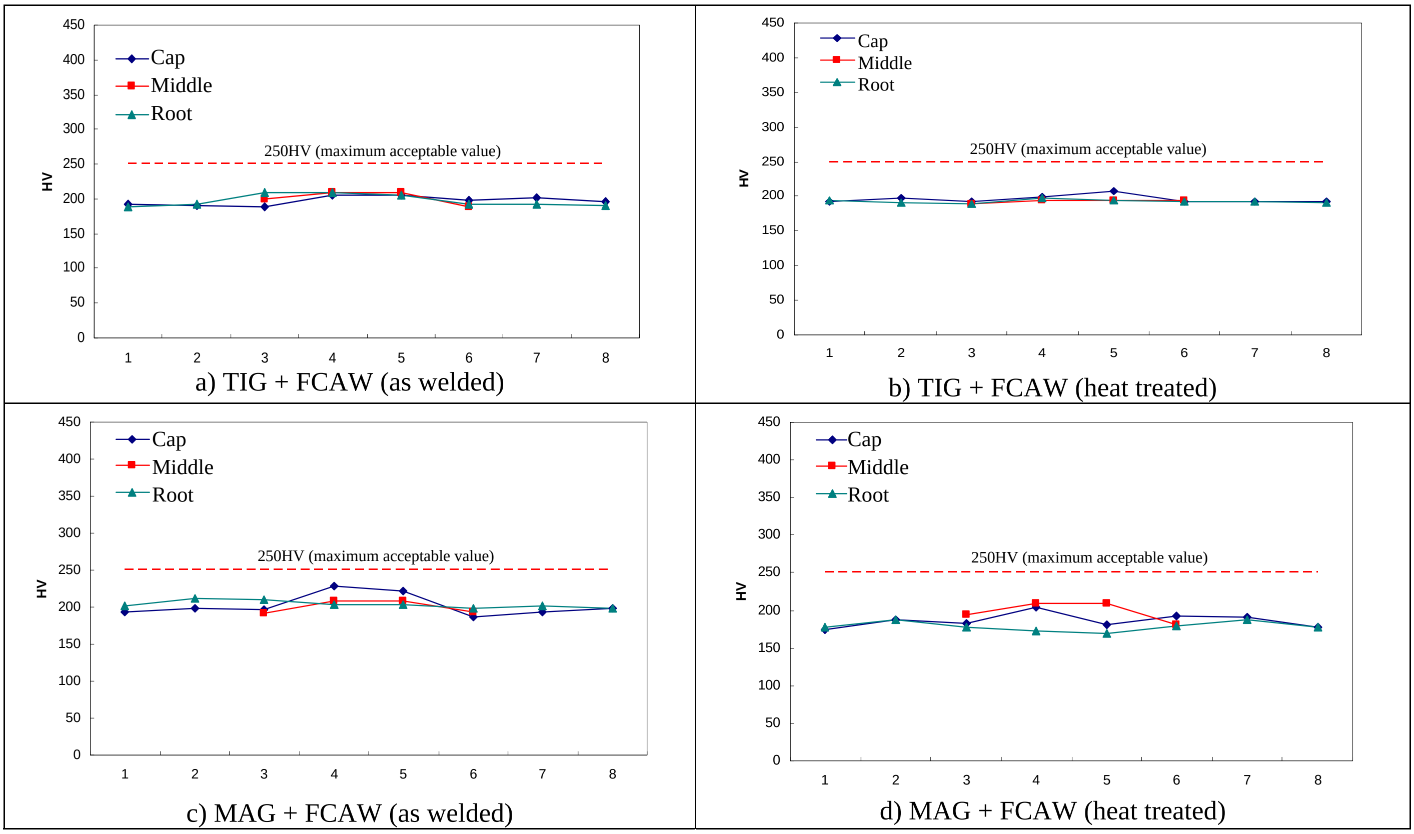


Figure 19. Hardness results of girth welds.

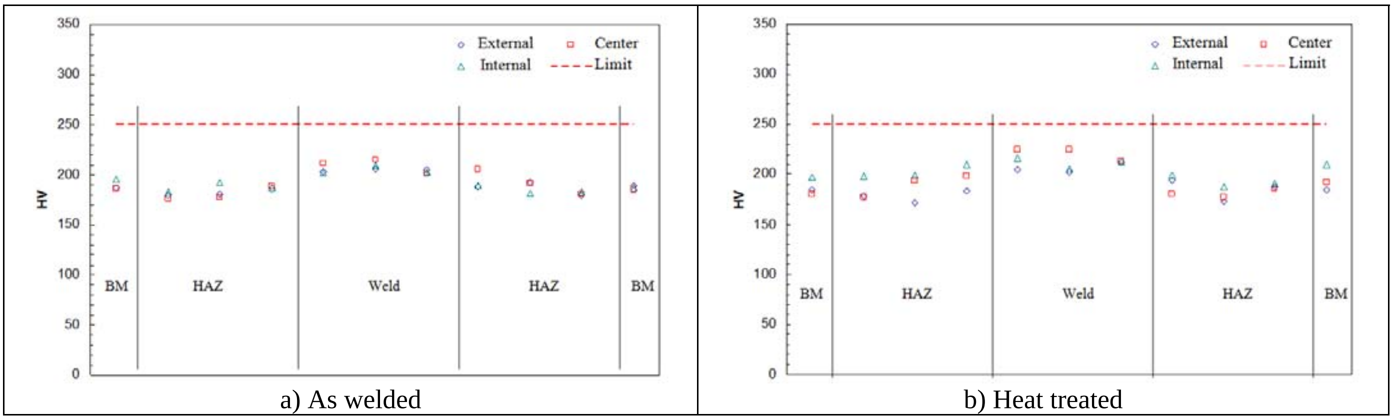
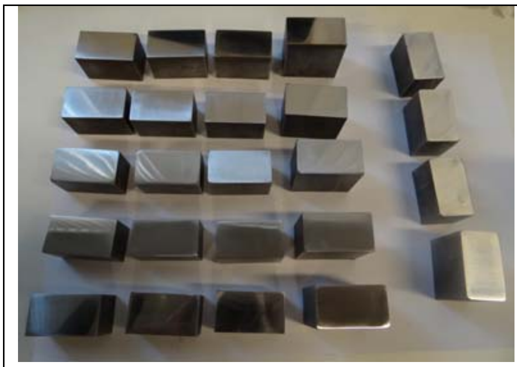


Figure 20. Hardness results of SAW longitudinal weld.



a) HIC specimens.

b) SSC specimens.

Figure 21. HIC and SSC test samples after the test.

Table 5 summarizes the results of CTOD test and compares them with the results from the fracture mechanics study that was done considering the presence of residual stresses (considering that the stress relieving heat treatment was not performed). Besides the residual stresses, all other stresses presented in the pipeline construction and operation were considered in the fracture mechanics study.

All test results from CTOD tests showed values above the minimum required by the fracture mechanics study. The results showed Table 5 are the lower results of all specimens of that girth weld.

Table 5. CTOD results.

	CTOD minimum required from fracture mechanics study (mm)	TIG + FCAW CTOD results (mm)	MAG + FCAW CTOD results (mm)
As welded	0,24	0,531	0,525
Heat treated	0,18	0,428	0,544

4. Conclusions

The stress relieving heat treatment, performed as specified by the design code ASME B31.8 and the Brazilian standard NBR 12712, results in a reduction of yield and tensile strength of the API 5L X65 sour service pipe, to values below the specified. According to the papers discussed in this study, pipes manufactured by UOE process with a chemical composition designed for sour service, are not suitable for stress relieving heat treatment.

The evaluation of girth welding without performing the stress relieving heat treatment showed that the required properties are within the specified limits. The welding procedure without heat treatment was qualified satisfactorily using two different processes and representing the same situation that will be faced in the field.

The use of heat treatment did not result in mechanical properties improvement. The Charpy test showed values of absorbed energy very close in as welded and treated condition (only the SAW longitudinal weld showed a reduction in absorbed energy after heat treatment). There was no significant change in hardness and no cracks were observed in the SSC and HIC tests.

The fracture mechanics analysis showed that the residual stresses existing due to the absence of heat treatment did not affect the integrity of the pipeline. Furthermore, the values of CTOD required with and without heat treatment are close and lower than that actually found in the girth welds tested.

The stress relieving heat treatment required by ASME B31.8 and NBR 12712 is not suitable for all types of pipes and is not essential for pipes with wall thickness above 1.25 inches. A comprehensive study shall be made before starting a pipeline construction with heat treatment in order to avoid low strength base metal properties around the girth weld.

5. References

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