DEVELOPMENT OF HIGH TOUGHNESS API 5L X70MS PIPE FOR OFFSHORE ULTRA-DEEP WATER APPLICATION

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Abstract

The exploration of oil and gas reserves of the pre-salt area at distant points from the Brazilian coast is bringing significant challenges to the national industry. Some fields are located approximately 250 km off the coast of Rio de Janeiro and are placed at 2500 meters depth, with forecasts to be up to 3000 meters, where the pipe strength becomes an important challenge due to present installation methods and due to the considerable load caused by the pipe weight resulting from the heavy wall thickness necessary to resist the external collapse pressure. Another important point is that, due to the hostile environment in which the new fields are placed it is necessary to develop new products in order to meet the rigorous mechanical and corrosion property requirements such as toughness, and corrosion resistance in the presence of H_2S. The need to produce and transport large volumes of gas under safe conditions demands the use of large diameter steel pipes produced by the UOE-SAWL process, which is a proven option that has already been applied in some important projects. Considering the above situation and the fact that nowadays the maximum pipe grade available to comply with the pre-salt gas pipeline requirements is X65, it is necessary to study and develop a higher pipe grade in order to reduce the wall thickness without reducing HIC resistance. This work presents the evaluation of mechanical properties and corrosion resistance in the presence of H_2S for OD of 20 inches, WT 25.4 mm APL 5L X70MS pipe. Very good Charpy and CTOD values (Charpy down to -60 °C and CTOD down to -20 °C) have been obtained and the pipes also have exhibited satisfactory results when submitted to HIC and SSC tests.

Introduction

Because of the constant necessity for material improvement imposed on the market by the oil and gas industry demands, efforts have been expended by the steel and tubular products manufacturers, in conjunction with research and development centers, to reach higher standards and satisfy new material requests.

The main goal of such efforts is to achieve steels with high strength and high toughness at low temperatures, complying with the American Petroleum Institute specifications [1]. Following this worldwide tendency, the Brazilian market presented a need to qualify API 5L Grade X70MS pipe for offshore application.

In addition to API specifications, the main offshore Brazilian projects also demanded compliance with special requirements including DNV-OS-F101, considering that the perspective is to apply such products in ultra-deep waters (operating depths up to 3000 meters). To make this qualification possible, an evaluation of UOE-SAWL API X70MS grade was performed aiming to comply with the requirements of the DNV-OS-F101 standard for sour service and additional requirements of the client for girth welding (more stringent sour service resistance after plastic deformation cycles). The results obtained for mechanical properties, SSC and HIC resistance are presented in this paper for the linepipe and girth weld joints for two heat input conditions.

High strength low alloy steels have been developed complying with API requirements, and prior testing proved that the pipe material exhibited satisfactory quality; however, the next great challenge was its application in the field as it involves welding with low heat inputs. Welding aspects deserve special attention because the majority of products obtained from such materials will be applied in production plants and transportation of oil and natural gas, which implies that these products will need to be welded to become pipelines [2]. The evaluation was focused on pipe weldability based on: base metal, the longitudinal weld and girth welds. The latter were produced to represent actual field welding conditions.

Furthermore, microstructural aspects regarding the influence of various alloying elements (nickel, chromium, molybdenum, vanadium, niobium, etc.) on the mechanical properties and SSC and HIC resistance of these steels has raised discussions and questions between engineers and researchers [3-5,7-9].

In order to achieve the desired properties, the steel was produced using state of the art technology in steelmaking, such as optimum rigorous alloy design, vacuum degassing, dynamic soft reduction, etc. The effects of these techniques, associated with Thermomechanical Controlled Processing plus Accelerated Cooling (TMCP+ACC) resulted in a higher strength and higher toughness with excellent weldability and sour service resistance.

Experimental Program

The pipes used for this development were produced at the TenarisConfab UOE-SAWL mill located at Pindamonhangaba City – São Paulo – Brazil. The plates were supplied by an internationally recognized plate mill. Girth weld joints were produced at TenarisTamsa Research and Development Center located in Veracruz City – Mexico.

Pipe Properties Evaluation

Chemical Analysis

Table I shows the minimum and maximum values obtained from chemical analyses of the pipes.

Table I. Chemical Analysis – Base Metal (wt.%)

Element	C	Mn	S	Si	P	N	Al	Ni	Cu	B	Nb+V+Ti	Cr+Mo+V	Pcm
Min	0.04	1.40	0.0007	0.30	0.007	0.004	0.025	0.008	0.012	0.0002	0.055	0.105	0.14
Max	0.06	1.54	0.0008	0.35	0.008	0.005	0.029	0.016	0.015	0.004	0.060	0.188	0.17

The chemical composition of the steel complies with the requirements of DNV-OS-F101 for DSAW 485 SFD pipe production. It can be observed that there is a very low quantity of carbon and alloying elements. Moreover, good practices of steelmaking and rolling processes combined with this steel composition provided refined microstructures, and were responsible for the high mechanical properties and good SSC and HIC resistance.

Macrostructure Analysis

A macrograph was taken from a flat section of the linepipe polished and etched by an appropriate reagent in order to analyze the appearance of the longitudinal weld with respect to requirements described in the DNV OS F101 standard.

Figure 1 shows the macrograph of the longitudinal weld. It is possible to observe the different areas present in the weld sample – weld metal, heat affected zone (HAZ) and base metal – as well as the presence of any defects or indication in the weld metal. In this case, no defects were found and the weld joint was approved.

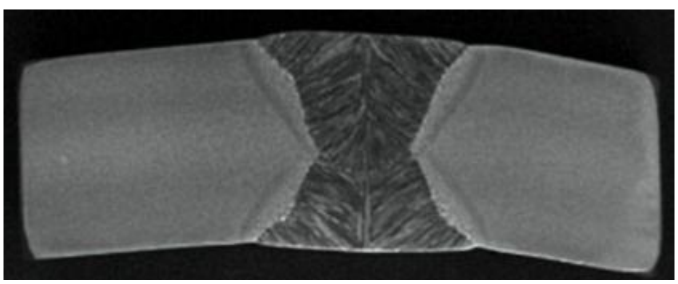
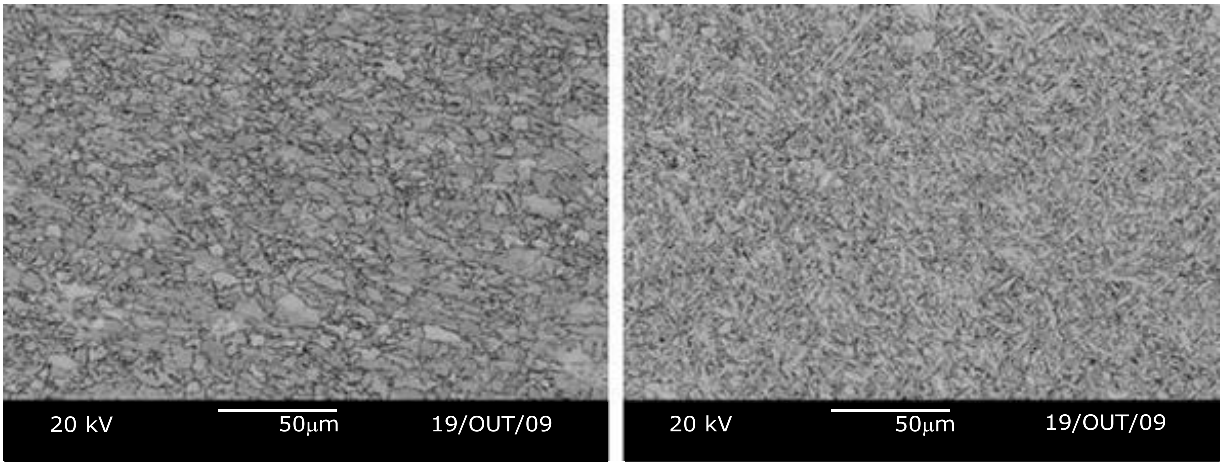


Figure 1. Weld macrograph – Magnification: x0.7.

Microstructural Analysis

The fine grained acicular ferrite and bainite present in the base metal produced high strength with good toughness and the low quantity of inclusions with a homogeneous microstructure suppressed the occurrence of HIC. Figure 2 shows the microstructures present in the pipe base and weld metal.

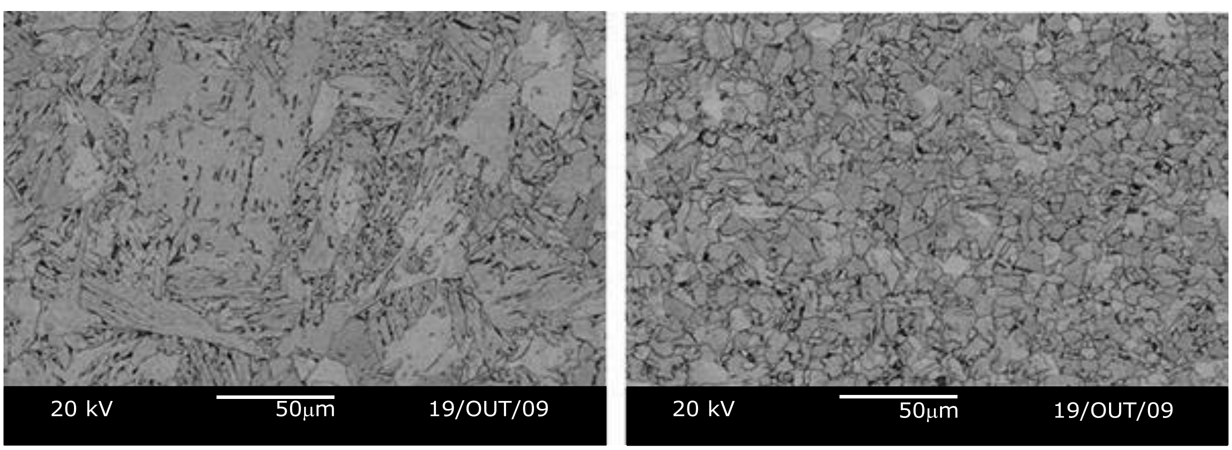


(a) (b)

Figure 2. Microstructures; (a) base material and (b) weld metal.

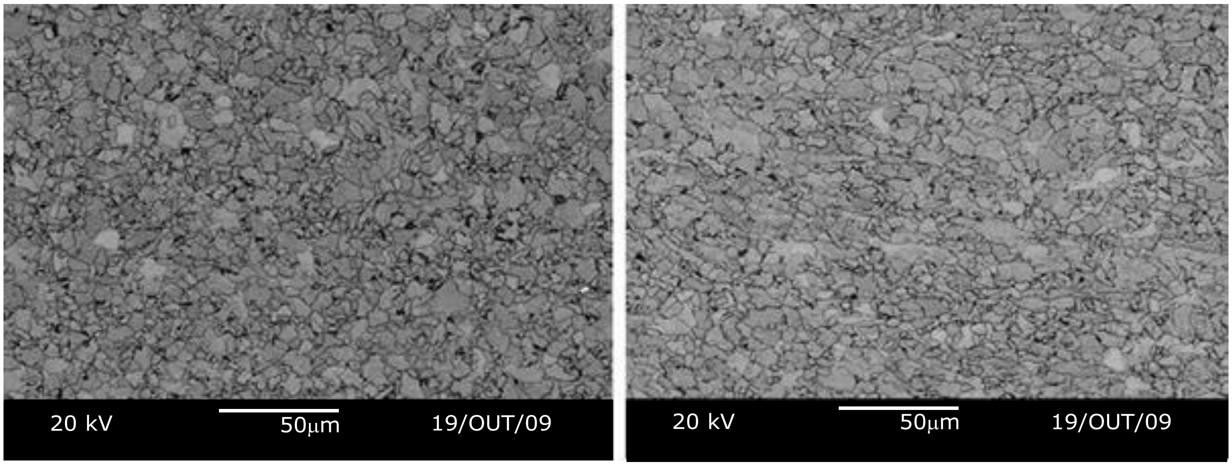
The microstructure of the weld metal was analyzed for the steel pipes presented in Figure 2. The weld has a primary microstructure characterized by acicular ferrite with no proeutectoid ferrite which explains the good toughness at low temperatures.

The HAZ microstructure is positively influenced by the fine microstructure obtained in the base metal. Figures 3 and 4 show the different microstructures in the HAZ according to the distance from the fusion line and the peak temperature reached during the welding cycle.



(a) (b)

Figure 3. HAZ microstructures; (a) coarse grain zone and (b) fine grain zone.



(a) (b)

Figure 4. HAZ microstructures; (a) subcritical zone and (b) intercritical zone.

Tensile Tests

In order to determine the mechanical properties of the linepipe, tensile tests were performed in the base metal and longitudinal weld, in accordance with DNV-OS-F101. Test samples were taken in the transverse direction of the linepipe at the following locations: longitudinal weld, 90° and 180° from the weld seam. Results obtained are presented in Table II.

Table II. Mechanical Properties of Base Metal

Position	YS(MPa)	UTS(MPa)	YS/UTS	El(%)
TT 90°	520	614	0.85	53.5
	546	612	0.89	53.9
TT 180°	502	599	0.84	54.7
	517	620	0.83	52.8
Weld	-	648	-	-
	-	646	-	-

Guided Bend Test

For guided bend testing, specimens were taken transverse to the longitudinal weld direction. The samples (side bend) were prepared in accordance with ASTM A 370. The tests were carried out and there was no evidence of cracks or ruptures in the parent metal, heat affected zone and weld metal or fusion line.

Hardness Tests

Hardness tests were performed in conformance with the ASTM E384 standard. To perform hardness measurements, Figure (H1b) of the ISO 3183:2007(E) standard was used as a reference. All specimens complied with the requirements of DNV-OS-F101 (250 HV 10 maximum). Figure 5 shows the average hardness variation throughout the samples.

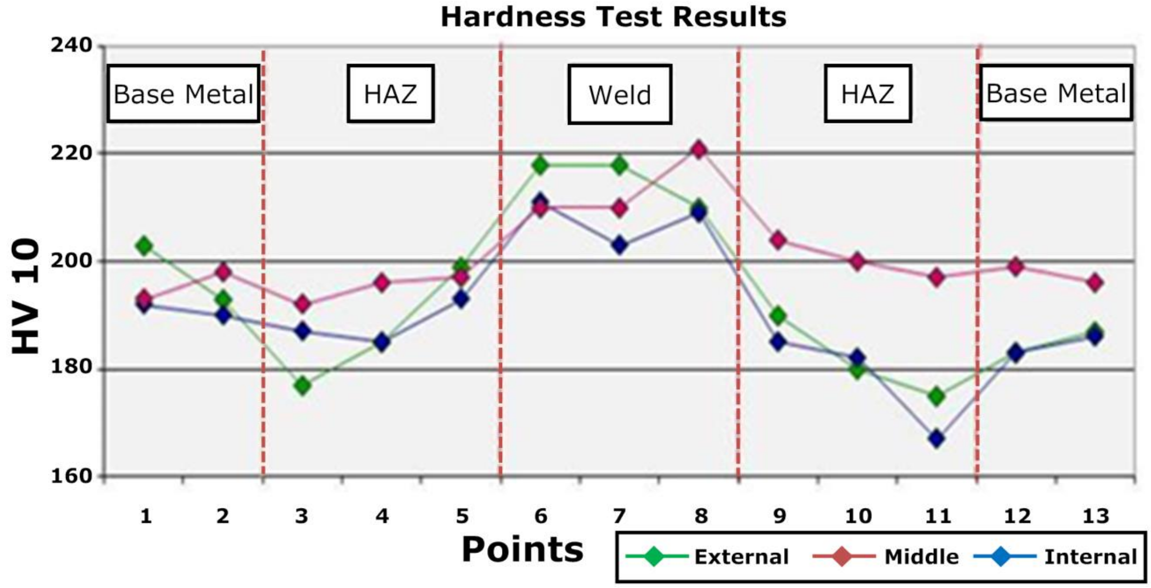


Figure 5. Hardness test results - longitudinal joint.

From the results presented above, it is possible to observe that values for all locations were below 250 HV 10 (requirement for sour service conditions), including the portion of the longitudinal weld.

Charpy V-notch Test

The Charpy V-notch tests were performed in accordance with ASTM A370. The tests were performed at different temperatures (23 ºC, 0 ºC, -20 ºC, -40 ºC and -60 ºC) and applied in the Base Metal, Fusion Line, Fusion line + 2 mm and Fusion Line + 5 mm. The tests were performed using sub-size specimens (10 x 5.0 x 55 mm) due to the load restrictions of the equipment used.

It is important to state that, from the 5 specimens tested in each condition, the minimum and the maximum values were eliminated, presenting thus three out of five values for each temperature and location. The Charpy values and the shear area are shown in Figures 6 and 7.

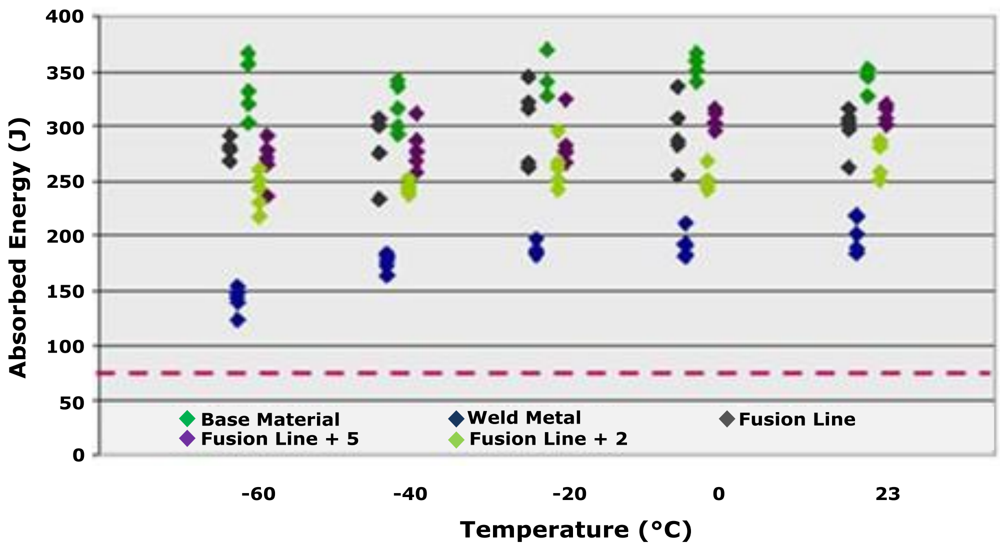


Figure 6. Charpy V-notch test results.

From Figures 6 and 7 it is possible to observe that the weld exhibits a good toughness (136 J absorbed energy at -60 °C with shear area above 70%). Regarding the HAZ, the absorbed energy is above 200 J in all the HAZ positions tested, from room temperature down to -60 °C with 100% of shear area, showing excellent HAZ toughness.

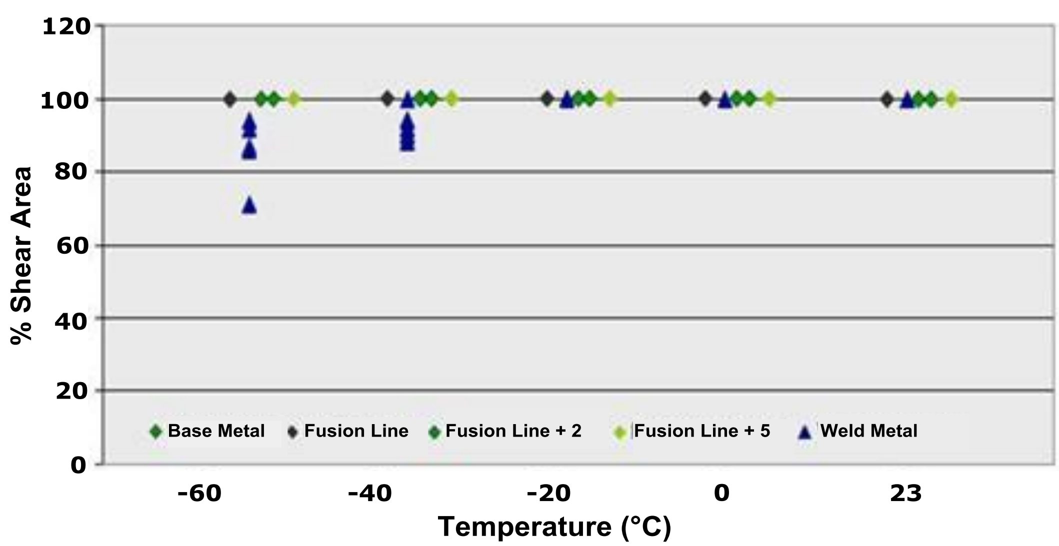


Figure 7. Shear area results from Charpy V-notch tests.

Sub-size energy values were converted to the full size specimen energy values shown in Figures 6 and 7 according to the equation presented in DNV OS F101.

Cracking Tip Opening Displacement – CTOD

The CTOD tests were carried out as per BS 7448 Parts 1 and 2. The tests permitted the analysis of the base metal, longitudinal weld center line and fusion line. The tests were conducted at two different temperatures: 0 ºC and -20 ºC. The specimen types tested were SENB (Bx2B) specimens. The results are shown in Figures 8 and 9.

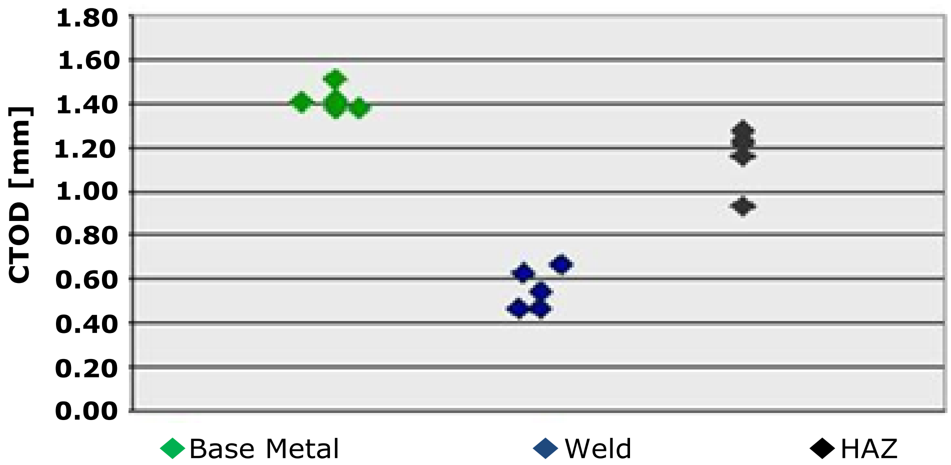


Figure 8. CTOD test results at 0 °C.

According to Figures 8 and 9, five CTOD specimens were tested at each temperature, for the base metal, longitudinal weld metal and HAZ. The results show values higher than the minimum specified by DNV-OS-F101 (0.20 mm), thereby confirming the good toughness behavior already shown in the Charpy tests.

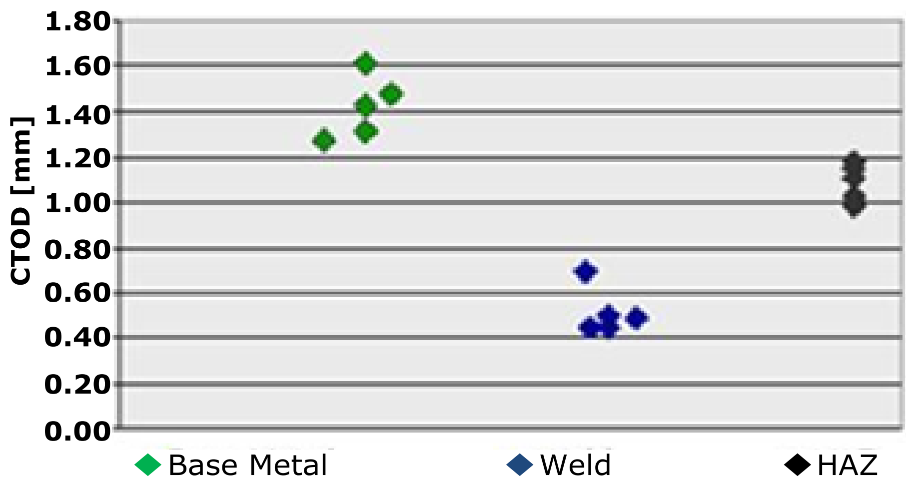


Figure 9. CTOD test results at -20 °C.

Sulfide Stress Corrosion and Hydrogen Induced Cracking Tests Results

Hydrogen Induced Cracking (HIC) tests were carried out in conformance with NACE MR0175 and NACE TM0284. The samples were taken according to the standard for DSAW linepipes and tested using the test Solution B of NACE TM0177. After examination no cracks were detected.

Sulfide Stress Corrosion cracking (SSC) tests were carried out in conformance with NACE MR0175 and NACE TM0177, and specimens were tested by Method A. The samples were taken from the longitudinal weld bead and at 90° and 180° from the weld and performed using the test Solution B of NACE TM177. During testing, no specimen rupture was found and subsequent examination confirmed no cracks in the specimens tested.

Girth Weld Evaluation

For evaluation of the girth weld properties of this new material under sour service conditions, two heat inputs were considered. The aim in this part of the qualification was to assess girth welding heat affected zone properties as described in the following paragraphs.

Welding Procedures and Specification

In order to perform the characterization of the girth weld HAZ and determine its properties, a welding heat input work window typically applied for offshore application welding processes was used. Thus, two different heat inputs representing typically the minimum and the maximum heat inputs of real operations were chosen.

Due to welding equipment characteristics in the field and with the focus on the heat input effect for the pipe girth weld HAZ, it was decided to use submerged arc welding (SAW) in order to produce the weld joints. In such a case, two small diameter wires were applied, combined with a low hydrogen flux and appropriate current, voltage and weld speeds in order to produce the weld joint with a minimum risk of discontinuities, mainly on the straight side of the joint (single bevel preparation).

The low heat input chosen was between 0.7 and 0.8 kJ/mm and the high heat input was between 1.2 and 1.3 kJ/mm. It was used with an API RP 2Z bevel design for all the welding tests as shown in Figure 10 to properly evaluate properties in the girth weld HAZ.

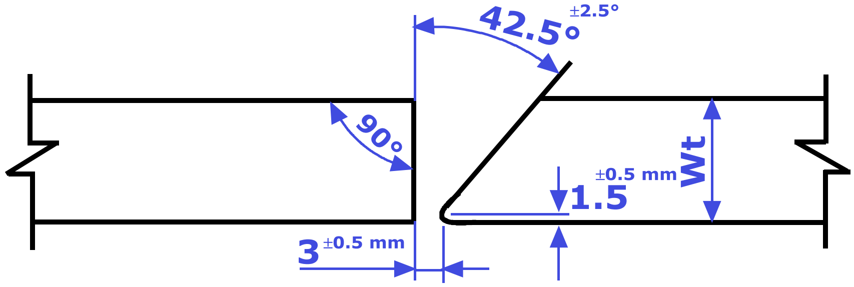


Figure 10. Diagram of bevel design.

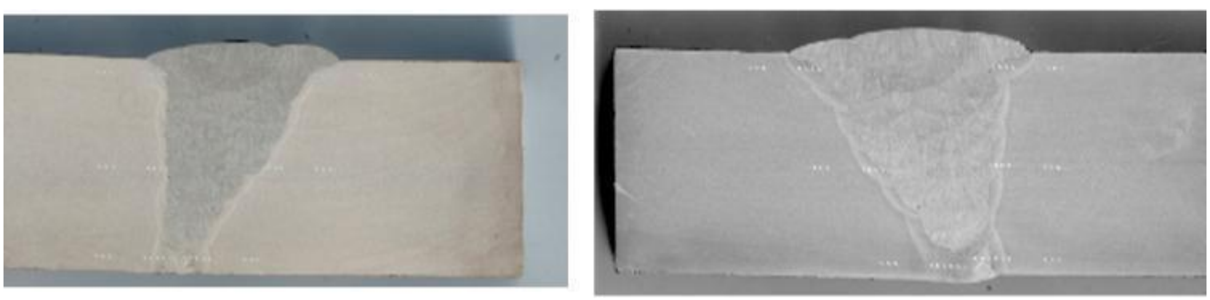
The challenge during this part of the qualification was to perform welding with this groove configuration: the major problems with this geometry were torch accessibility and cleanness between passes in multiple pass welding. Care was taken during operation to avoid any discontinuity and defects.

Mechanical Properties Evaluation

Mechanical tests for both heat inputs were performed in order to evaluate the properties of the HAZ of the girth welded pipes.

Macrostructure Analysis

Macrographs were performed in order to analyze and record the appearance at both heat inputs, of weld joints and weld metal. As expected, it should be noted that the high heat input sample produces wider HAZs compared with the low heat input welds. Both macros show that a straight side with a homogeneous HAZ was achieved in both heat input weld joints, thus it was possible to perform Charpy V-notch and CTOD tests in those areas of concern without interference of the weld metal. Figure 11 shows macrographs of the weld joints for both heat inputs.



(a) (b)

Figure 11. Macro sections; (a) Low heat input (Magnification: x0.7) and (b) High heat input (Magnification: x0.7).

Tensile Tests

For the tensile tests, 3 samples were taken from the transverse direction with respect to the girth weld. All samples failed in the parent metal, leading to the conclusion that strength properties of the weld and HAZ were superior when compared with the base metal (not heat affected material).

Guided Bend Tests

For guided bend tests, two samples transverse to the direction of the girth welded joint were tested for each heat input. Test specimens were prepared according to ASTM A 370. No cracks or ruptures were evident in the weld metal, HAZ (especially fusion line) and parent metal (longer than 3.2 mm) were detected, even for the straight side of the weld joints.

Hardness Tests

For each heat input, Vickers hardness traverses were also performed according to Figure 10(c) from APPENDIX B of DNV-OS-F101. Two samples in the same welded ring were analyzed. The results obtained for both heat inputs are shown in Figures 12 and 13.

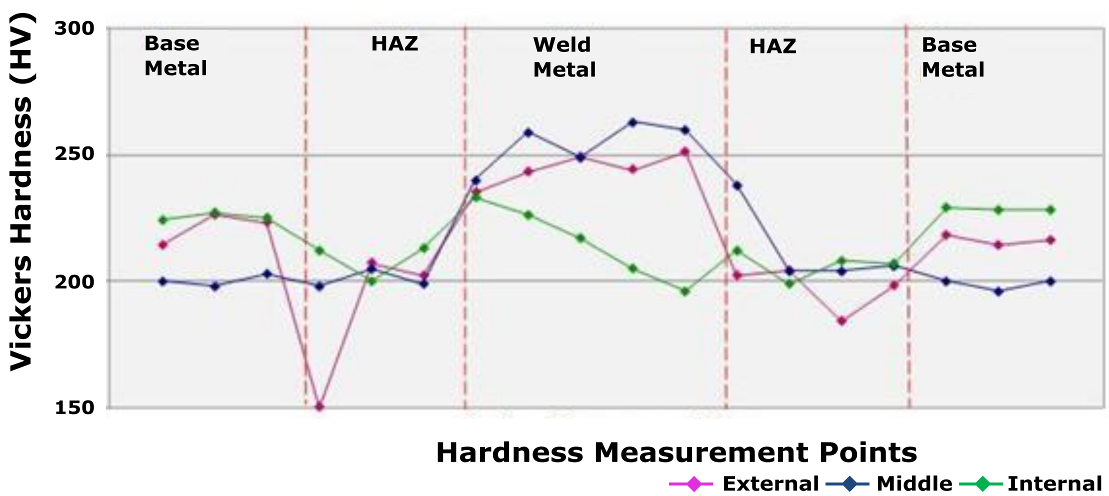


Figure 12. Hardness results using low heat input.

From Figure 12 it is possible to observe that all base metal and heat affected zone results were below 250 HV 10 (sour service condition maximum) using low heat input. The girth weld exhibited some points above this threshold; however, weld metal was not the focus of this investigation and could be later optimized through proper flux/wire selection.

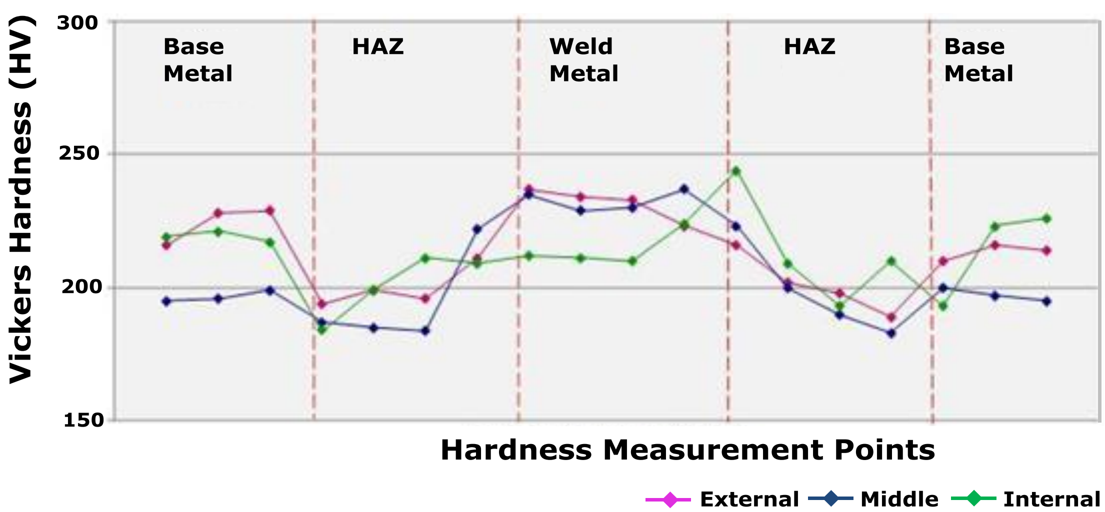


Figure 13. Hardness results using high heat input.

From the results presented in Figure 13 it is possible to observe that all base metal and heat affected zone results were below 250 HV 10 (sour service condition maximum) using high heat input.

Charpy V-notch Tests

The Charpy V-notch test specimens were taken from different regions of the girth weld HAZ for each heat input. Notch locations were placed in three different regions of the HAZ: Fusion Line (FL), Fusion Line + 2 mm (FL+2) and Fusion Line + 5 mm (FL+5). For each of these regions, at each heat input, 5 specimens were tested at the following temperatures: 27 °C, 0 °C, -20 °C, -40 °C and -60 °C.

Following DNV-OS-F101 and Petrobras special requirements, all tests were performed with full size specimens (10 x 10 x 55 mm). The results obtained are shown in Figures 14 and 15.

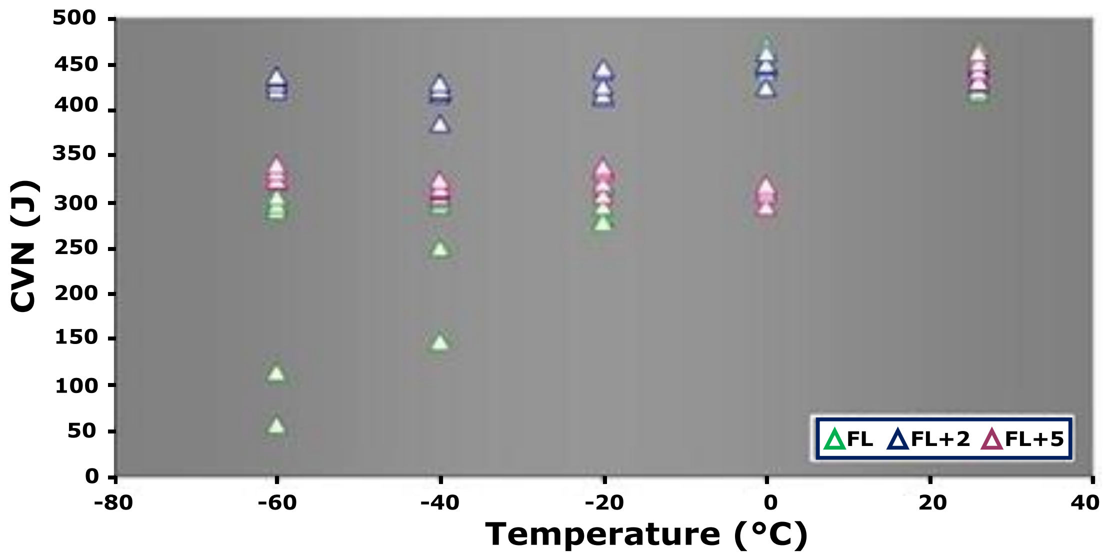


Figure 14. Charpy test results from girth weld using high heat input – X70MS.

For both heat inputs and all locations, absorbed energy values were very good (minimum 126 J at -40 °C) except at -60 °C, where specimens exhibited energy values less than 50 J at the fusion line. This was associated with a small lack of fusion detected at the fusion line after the Charpy test.

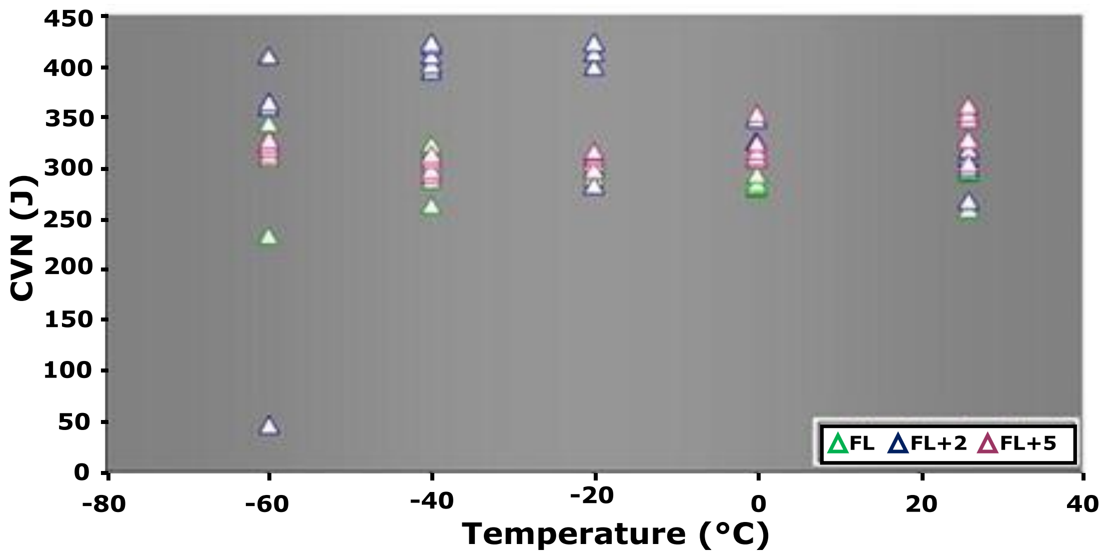


Figure15. Charpy test results from girth weld using low heat input – X70MS.

CTOD Tests

For CTOD tests, two sets of five specimens were tested for each heat input. The tests were carried out at two different temperatures, 0 °C and -20 °C. The criteria established for validation was a CTOD value greater than 0.15 mm. Tables III and IV present the CTOD values obtained. Results were all above the minimum required.

Table III. CTOD Results Using Low Heat Input

Pipe and Position	**Temp.**	**CP**	**CTOD [mm]**	**Fracture type**	**Pipe and Position**	**Temp.**	**CP**	**CTOD [mm]**	**Fracture type**
LS-3089 LHI	0 °C	LHI 1	1.30	δm	LS-3092 LHI	-20 °C	LHI 1	0.50	δc
		LHI 2	1.30	δm			LHI 2	0.81	δm
		LHI 3	1.29	δm			LHI 3	0.20	δc

Table IV. CTOD Results Using High Heat Input

Pipe and Position	**Temp.**	**CP**	**CTOD [mm]**	**Fracture type**	**Pipe and Position**	**Temp.**	**CP**	**CTOD [mm]**	**Fracture type**
LS-3049 HHI	0 °C	HHI 1	0.78	δm	LS-3082 HHI	-20 °C	HHI 1	0.52	δm
		HHI 2	1.32	δm			HHI 2	0.25	δc
		HHI 3	0.44	δm			HHI 3	0.24	δc

The tested CTOD geometry was Bx2B according to BS 7448 Part 2 with highest thickness possible and the notch located at the fusion line with T-T orientation and crack plane orientation NP.

SSC Corrosion Tests

SSC corrosion tests were performed using four point bend (FPBT) specimens and according to the ASTM G-39 standard using test Solution A of NACE TM 0177. The testing duration was 720 hours and the stress applied was 100% of the minimum value of yield stress obtained during the tensile tests for base material evaluation (in this case, 520 MPa). A set of 3 specimens was tested for each heat input. Specimens were taken as close as possible to the internal surface of the linepipe. Results obtained are shown in Tables V and VI.

Table V. Four Point Bend Test Results Using Low Heat Input

Identification		**Initial Values**		**Final Values**		**Stress Applied**	**Results**
Sample	**Specimen**	**Saturation ppm**	**pH**	**Saturation ppm**	**pH**	**%AYS**	
LS-3097 LHI	1	2520.44	2.65	2673.71	3.48	100	No Failure
	2	2520.44	2.65	2673.71	3.48	100	No Failure
	3	2520.44	2.65	2673.71	3.48	100	No Failure

Table VI. Four Point Bend Test Results Using High Heat Input

Identification		**Initial Values**		**Final Values**		**Stress Applied**	**Results**
Sample	**Specimen**	**Saturation ppm**	**pH**	**Saturation ppm**	**pH**	**%AYS**	
LS-3096 HHI	1	2520.44	2.65	2673.71	3.48	100	No Failure
	2	2520.44	2.65	2673.71	3.48	100	No Failure
	3	2520.44	2.65	2673.71	3.48	100	No Failure

The conclusion is that the HAZs of this material, welded with the investigated range of heat inputs and tested according to the standard at 100% of actual yield strength are resistant to SSC according to the criteria of NACE TM 0177 when tested in Solution A.

Conclusions

A complete evaluation of linepipe mechanical properties and SSC and HIC resistance was performed for API 5L X70MS linepipe, considering base material, HAZ and longitudinal weld joint. The results complied with strict requirements according to DNV-OSF-101, NACE TM 0284 and NACE TM 0177 standards and well beyond special requirements imposed by Petrobras.

In addition evaluation of linepipe girth welding, especially HAZ, for two heat inputs commonly applied in offshore girth welding application was carried out. Mechanical properties of the HAZ were performed and the results also comply with the strict requirements. Excellent fracture toughness properties and SSC resistance were achieved in the girth weld HAZ areas showing the acceptability of the product for higher requirements application.

Considering offshore installation, this work will be continued in order to study pipe and girth weld behavior after plastic deformation and ageing.

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