GEOMETRY COMPARATIVE ANALYSIS OF A WELDING JOINT PROCESSED BY FCAW IN THE API 5L X 80 STEEL

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Abstract. *The influence of the geometry in the welded joint processed by FCAW with different welding parameters was studied. The base material API 5L X80 steel, having two Bisel angle (25° and 35°), was welded by using the E71T1 flux cored wire as consumable. As a starting point, the process of welding was initiated with the short-circuit current for each Bisel angle of the joint. Following this initial condition, the current was raised to modify the transfer mode of metal of short-circuit for globular. For each Bisel angle, the influence of the welding parameters was studied. The quality of the welding was evaluated by mechanical properties and the extension of HAZs. The microstructures were characterized by optics and scanning electron microscopy, in which were made comparative analysis of the microstructural constituents in cross section of the test samples. The mechanical properties for each welding condition were evaluated by uniaxial tensile tests, bending tests and hardness measurements allowing comparison between different parameters. The results showed that the welding energy and the geometry of joint (Bisel angle) influenced the size of heat affected zones and the associated mechanical properties. The results obtained with the smallest angle of Bisel (25º) were better than the results obtained with greater angle (35º). In addition the results showed that even the consumable having less resistance than the base metal did not affect the properties and quality of the welded joint. The development of this work provided a significant technological contributions, in recent welding process of API 5L X80 steel for use of oil and gas transport in Brazil.*

***Keywords**: API 5L X80 Steel; FCAW Process; Welding Parameters; Mechanical Properties.*

1. INTRODUCTION

Until the 70s, the high-strength steels were produced by hot rolling process, followed by normalization. Since the 70s with the introduction of thermomechanical controlled processes, it was possible the production of quality steel API 5L (2007), with reduced carbon contents and hardened by the addition of alloying elements, niobium and vanadium (Fedele, 2002). In Brazil, according to Bott et al (2005), manufacturing equipments have limitations to achieve a cooling rate required to obtain a refinement of grain such as required for the steel grade API 5L X 80. This steel was produced with a different chemical composition in order to reach the minimum requirements for this degree. For this alloying elements such as niobium, chromium, vanadium and molybdenum were added.

The welding processes used in these steels has been conservative. In this same vein the authors Hillenbrand et al. (1997), cite two welding procedures for steel X 80, developed by Ruhrgas AG and Mannesmann Anlagenbau together with European manufacturers of consumables: Manual welding in vertical down electrodes combined and Mechanized GMAW welding with narrow openings, vertical down.

Following Quintana and Johnson (1999), the fabrication of a welded joint using a single consumable is usually not practical or cost-effective low. For example, many online pipelines are produced using SMAW in root pass and FCAW-S for filler passes. Manufacture of large compositions or structures normally involves welding using either GMAW and FCAW-G processes in industries or SMAW and FCAW-S processes in the field. The welding processes of tacking and adjustment are usually made by SMAW, and the rest of the structure another welding processes is used to achieve higher deposition rates. These are examples of applications where mixtures of different weld metals can occur in a single joint. These examples indicate that a mixture of different filler materials and process occurs frequently as a normal part of the manufacturing process. In contrast, many welding consumables are optimized without considering dilution effects underlying base metal or different chemical compositions of the weld metal.

Graf and Niedorhoff (1995) take into account the performance of circumferential welds overmatched and undermatched in plates for testing. The results suggested that it is acceptable to make circumferential welding with cellulosic electrodes of type AWS E 9010-G X 70 degree, and some cases in grade X 80. A method of welding joints was developed by Mannesmann in cooperation with consumables' manufacturers. That method consists of root pass with cellulosic electrodes and filling and sealing passes with AWS E 10018-G which showed well suited for the laying for X-80 and A 550 GRS steels.

In his review, Loureiro (2002) said that welding joints (WJ) are naturally heterogeneous materials, exhibiting variations in the microstructures and mechanical properties (hardness, strength and toughness) through the welding metal (WM) and heat affected zone (HAZ). A phenomenon of mixing of different weld metals and dilution on WM and complex thermal cycles induced in HAZ motivates this (Quintana and Johnson, 1999; Loureiro and Fernandes 1994). WJ's performance seems to depend on the size and level of disagreement on the strength and toughness of each area of the WJ (Toyoda et al, 1994). It is customary to classify the welds as overmatched, evenmatched or undermatched, if the value of yield strength or ultimate stress of the WM is respectively greater, equal or inferior to the BM (base metal). Overmatched welding is commonly used in structural components under stress (AWS D1.1, 1995). Undermatched welding is sometimes used in structural joints of high strength steel in order to minimize the tendency to hydrogen-induced cracking, reducing or preventing additional cost with preheating

In this work the properties of joints welded by FCAW-G process were studied. This process used two different geometries of joints welded with undermatched WM under different welding currents. The main objective was to study the effect of welding procedures in the microstructures and mechanical properties of welding undermatched and analyze their influence on the performance of welded joints using only a type of consumable.

2. MATERIALS AND METHODS

2.1. Materials

The base metal was obtained from rings of steel pipe API 5L X80, having 864 mm (34 ") of nominal diameter and 19 mm thickness. These rings were cut from different samples of steel tubes produced by controlled rolling without accelerated cooling (TMCP - thermomechanical controlled process). The chemical composition, mechanical properties are in Tabs. 1 and 2, the chemical composition of weld metal is in Tab. 3.

Table 1. Chemical composition of the base metal, as API 5L/ASTM A 751(CONFAB, 2008).

Chemical elements (wt %)							
C	S	N	Al	Si	P	Ti	V
0.02 - 0.03	0.003 - 0.004	0.0054 - 0.0059	0.027 - 0.032	0.17 - 1.24	0.013 - 0.018	0.013 - 0.017	0.023 - 0.026
Cr	Mn	Ni	Cu	Nb	Mo	B	Ca
0.158 - 0.066	1.72 - 1.78	0.013 - 0.14	0.008 - 0.010	0.060 - 0.072	0.183 - 0.192	0,0001 - 0.0002	0.0024 - 0.0032

Table 2. Records of Mechanical Testing of the pipe, according to API 5L/ASTM A370 (CONFAB, 2008).

Yeld Point – YE (MPa)	Tensile Strength – TS (MPa)	Value LE / LR	Elongation (%)	Tensile Strength in weld (MPa)
570 - 586	719 - 726	0.79 - 0.81	33.3 - 37.0	709 - 720

Using the recommended equations by the International Institute of Welding (IIW) and the standard API 5L (2007) for steel and building on the chemical composition of the base material, Tab. 1, were obtained the values (modified cracking parameter) P_{CM} = 0.15, 0 , 15, and 0.15 and (equivalent carbon) CE = 0.40, 0.40 and 0.39, respectively in three different samples of tubes. The consumable wire electrode used for FCAW-G process was E71T-1C, with a diameter 1.2 mm, according to AWS A5.20 or ASME SFA-5.20. The chemical composition and mechanical properties of the wire as welded are shown in Tabs. 3 and 4 respectively, according to information from the manufacturer's catalog and AWS A5.20 (2005).

Table 3. Chemical composition of weld metal as welded tubular wire E71T-1C (After CONFAB).

Elements (wt %)				
C	Si	Mn	P	S
0.03	0.51	1.26	0.010	0.011

Table 4. Mechanical properties of weldig metal (WM) E71T-1C in "as welded" condition.

	Yeld Point – YE (MPa)	Tensile Strength – TS (MPa)	Elongation (%)	Temperature (ºC)	Charpy V (J)
Manufacturer	545	572	28	0	160
				-20	70
AWS A5.20	390	490 - 670	22	-20	27

2.2. Welding procedure

The rings were provided with bisel angles of 35° at the sheet board, the most suitable joint to obtain a good root pass with a nose from 1.5 to 2.0 mm in height, with 2.0 to 2.5 mm. From these rings, samples were taken (plate test) for longitudinal welding, keeping the dimensions of the bisel angle, two with the same bisel angle and two others with bisel angle of 25°. Figure 1 details the geometry of the joint used.

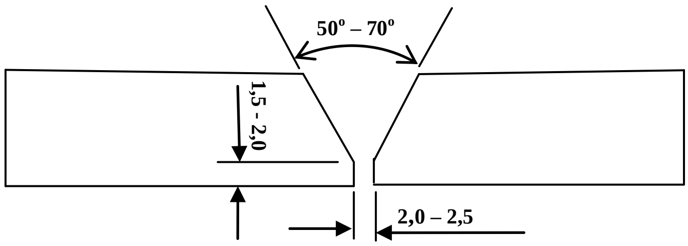

Figure 1. Geometry of joints, dimensions in mm.

Table 5 presents the specifications for welding procedures, following ASME-IX (2001). In these specifications, procedures were used to change the welding parameters for the geometry of the groove, welding current and arc voltage. Even with these changes, were tried to keep the welding parameters used within the ranges recommended by the manufacturers of wire consumables.

Table 5. Specification for Welding Procedure FCAW-G.

Weld condition	G-1	G-2	G-3	G-4
Bevel angle	25º	35º	25º	25º
Polarity	CC^+	CC^+	CC^+	CC^+
Current (A)	112 - 168	164 - 210	112 - 168	164 - 210
Voltage (V)	26 -27	28.8 – 29.2	26 -27	28.8 – 29.2
Heat input (kJ / mm)	0.4 – 1.2	1.0 – 2.5	0.4 – 1.2	0.5 – 2.0
Shielding gas	100% CO_2	100% CO_2	100% CO_2	100% CO_2
Gas flow (l / min)	16-20	16-20	16-20	16-20
Wire speed (m / min)	5 - 8	7 - 10	5 - 8	7 - 10
Welding speed (mm / s)	2 - 7	2 - 7	2 - 7	2 - 7
Extension of wire (mm)	9 - 12	9 - 15	9 - 12	9 - 15
Welding position	plain	plain	plain	plain
Maximum interpass temperature	150 º C	150º C	150 º C	150º C

The welding was performed based on these procedures and a qualified welder was selected in order to obtain the transfer mode for short circuit. Interpass temperatures were obtained using an optical pyrometer with adjustable permittivity about 0.1 ° C. The length of the consumable wire was measured with a measuring tape with smallest division of 1 mm. The welding speed was calculated by measuring the time of each pass, with a stopwatch, dividing by the distance traveled. The heat input was calculated based on Eq. (1), considering the thermal efficiency of the process as $\eta = 0.70$, where V is voltage, I the current and v welding speed.

$$H = \eta \frac{V.I}{v} \tag{1}$$

2.3. Microstructural characterization

Each sample was prepared by traditional metallography using sandpaper with particle size of 220, 320, 400, 600 and 1000 mesh. During sanding, changes in the direction of grinding of 90 ° were made to prevent loss of flatness. Finally the surfaces were polished using diamond paste of 1 micron. Chemical attack was made by Nital 5% during 5-10 seconds. Microstructure characterizations were performed using an optical microscopy with magnification of 50 up to

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1,000 times or scanning electron microscopy with magnifications of 1,000 up to 10,000 times. Macroscopic analysis was performed with the aid of a stereoscope.

2.4. Mechanical testing

For each welding condition, two test specimens with reduced cross-sections were prepared, according to ASME IX (2001). The specimens were tested in uniaxial tension in a universal testing machine with a speed of 1 mm / min, the orientation of the ABNT NBR 6152 (1992).

For bending test, six specimens for each welding condition were prepared with a cross section of 10 x 19 mm, according to ASME IX for conducting the test according to the guided bending following positions: cross-sectional view, transverse and lateral root cross. The test was conducted in a press where the material was shaped plastically until the specimen reached 120 degrees or broke before then.

The same specimens used in the tests for metallographic microstructural characterization were subjected to microhardness test, following ASTM E384-05 (2005). A load of 300 grams and an indentation time of 20 seconds were used for an image magnification of 40 times. The microhardness was taken in cross-section of the specimen at a point in the weld fillet and six on each side at distances of 2.5 mm, considering the centerline of the weld at a distance of about 3 mm from the surface.

The Charpy impact tests were performed according to ASTM A 370 (2004) and the specimens machined according to ASTM E 23 (2002). The tests were performed in the range of energy absorption up to 300 J. The specimens were tested at temperatures of 0 º and 25º C (ambient). For the temperature of 0º the specimens were kept in a bath of brine cooled to a temperature of around - 10° C for a time of 10 minutes, so removed from container until the temperature reaches 0º ± 1° C. Temperature control was accomplished using an optical pyrometer with adjustable permittivity.

Samples were extracted from two different regions: one from the weld metal (WM) and another from HAZ. All these specimens were removed from the center of the cross section of the weld, the notch being located in the center of the weld metal in the thickness direction of the weld. The specimens obtained for the HAZ were located at half the thickness of the weld and the notch was located between the fusion line (FL) and the edge of HAZ.

3. RESULTS AND DISCUSSION

3.1. Welding Performance

Based on monitoring reports, the welding parameters for each welding condition were summarized and are presented in Tab. 6.

Table 6. Summary of monitoring welding conditions.

Welding condition	Number of passes	Variation of heat input (kJ/mm)	heat input per pass average (kJ/mm)	Time of welding (s)
G-1(35º)	13	0.40 – 1.15	0.85	862.0
G-2(35º)	7	0.90 – 2.60	1.63	865.0
G-3(25º)	11	0.40 – 1.00	0.50	663.0
G-4(25º)	8	0.50 – 1.70	0.70	496.0

It is observed that the welding condition G-2 (35) demanded greatly heat input (1.63 kJ / mm), in which the welding was in 7 passes with lower welding speed. This can be observed when compared with G-1 (35) and G-4 (25). G-1 (35) of the same geometry of joint, 13 passes with welded in welding speed approximately equal to G-2 (35). G-4 (25), the same parameters specified in G-2 (35), but with minor groove, was welded with approximately the same amount of passes. The variation of welding speed between the other conditions was not significant to justify substantial variations in the thermal contributions.

In general it can be observed that the welding time was shorter for the conditions of lower angle (25 °).

3.2. Macro and microstructural analysis

Optical microscopy was performed under the conditions of the welding in fusion zone, regions of the face, root, center, FZ interface / base metal and HAZ. Figure 2 A and B shows coarse grain of ferrite matrix, FZs of the G-2 and G-3 conditions, respectivily. All figures show slightly enriched ferritic grains with pearlite boundaries.

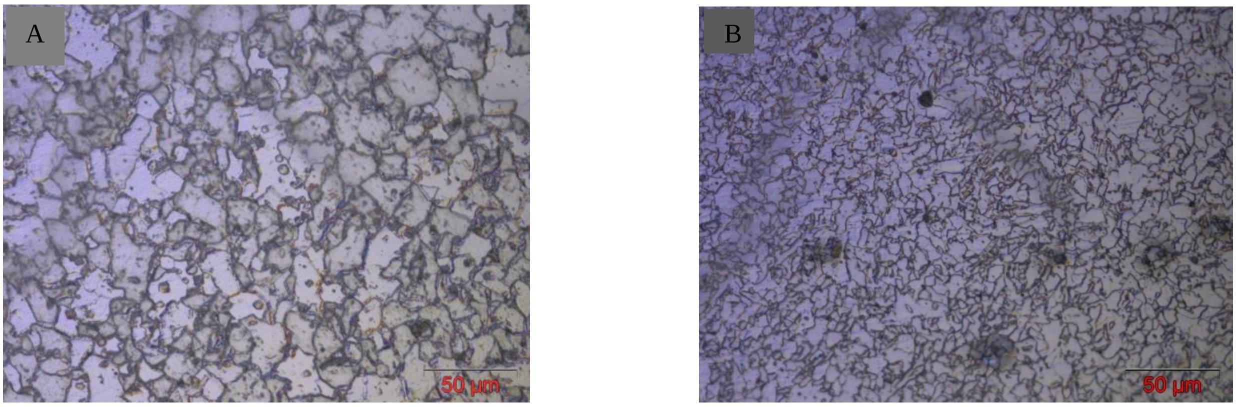

Figure 2. A) Fusion zone, G-2. B) Fusion zone, G-3.

The influence of heat input during welding can be clearly observed in these figures shown above. In Figure 2A, the G-2 condition (1.63 kJ / mm) has grain size about 40 microns, while in Fig. 2B, the G 3 condition (0.50 kJ / mm) has grain size about 10 µm.

The microstructure characterization was performed by scanning electron microscopy (SEM) for different conditions of welding of the base metal in the regions as heat affected zone and fusion zone link. All figures show a general ferritic microstructure with a weak pearlite content in the grain boundaries.

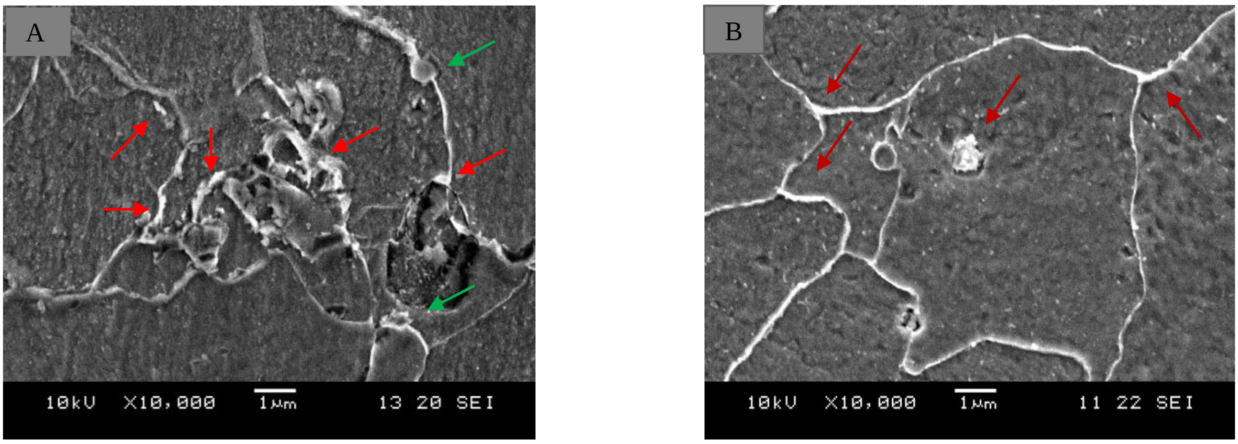

Figure 3. A) Fusion zone, G-1. B) Fusion zone, G-2.

Figure 3 A and B shows a small content of M-A (Martensite-Austenite) constituents present at grain boundaries (red arrows) and retained austenite (green arrows). One can also observe the influence of heat input, ZF G-2 (1.63 kJ / mm) has grains larger than the FZ-G 1 (0.85 kJ / mm).

The macrographs are shown in Fig. 4 A and B. The condition G-2 presents a discontinuity between the root and sealing passes.

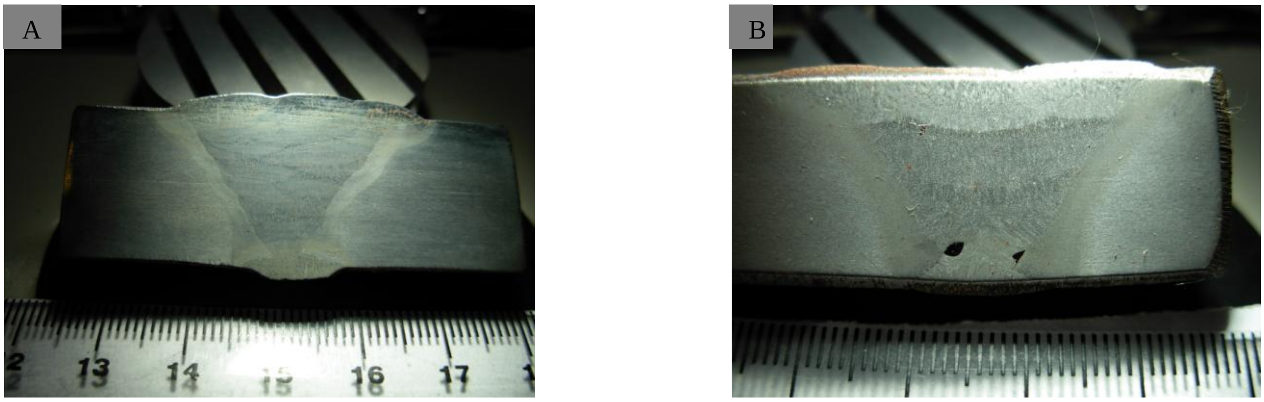

Figure 4. A) Macrography condition G-1. B) Fusion Zone G-2.

Measurements of HAZ widths were made as a function of the the heat input average, Tab. 7.

Table 7. Comparison between HAZ width as a function of heat input conditions.

Weld condition	G-1	G-2	G-3	G-4
HAZ width (mm)	2.0	2.4	1.8	1.6
Average heat input (kJ/mm)	0.85	1.63	0.50	0.70
Variation in heat input (kJ/mm)	0.40 – 1.15 (0.75)	0.90 – 2.60 (1.70)	0.40 – 1.00 (0.60)	0.50 – 1.70 (1.20)

The condition G-2 had a higher heat input average per pass, justifying its greater width as compared with the others. It is observed that the HAZ widths follow the magnitude of thermal average of the contributions. These values were influenced by operational factors.

3.3. Mechanical testing

For analysis of the mechanical properties the samples were extracted from the welded test plates and subjected to uniaxial tensile tests, results in Tab. 8.

Table 8. Results of tensile tests

SWP test specimen	Yeld strength (MPa)	Tensile strength (MPa)	Deformation (%)	Region of the rupture
G 1.1	510.00	544.00	20.33	Broke in the welding
G 1.2	512.00	544.50	20.28	Broke in the welding
G 2.1	415.30	513.80	15.44	Broke in the welding
G 2.2	418.66	499.11	15.54	Broke in the welding
G 3.1	464.99	523.46	16.43	Broke in the welding
G 3.2	457.58	492.97	18.68	Broke in the welding
G 4.1	384.94	519.22	21.78	Broke in the welding
G 4.2	424.41	503.87	20.96	Broke in the welding

Following API 5L (2007), values for yield strength is 550 MPa and for tensile strength is 620 MPa and the manufacturer's values as in Tab. 2. Values of the manufacturer's catalog and AWS A5.20 (2005), for consumable are described in Tab. 3. For each welding condition, bending tests were carried out following guided positions: cross-sectional view, transverse root and four lateral bending (Tab. 9). In these test, ASME - IX (2007), after bending specimens should not have opened discontinuities in the weld metal or HAZ exceeding 3.2 mm, measured in any direction on the convex surface of the specimen.

Table 9 - Results of Bending Test Conditions.

Weld condition	Root bend	Bend face	Bend side
G-1	Broke in the welding	Broke in the welding	Good for all specimens
G-2	Broke in the welding	Broke in the welding	Good for all specimens
G-3	Good	Good	Good for all specimens
G-4	Broke in the welding	Good	Good for all specimens

Although some samples have shown non-conformities in the folds of the face and root, should take into consideration that the folding predicted by the standard for plate thickness of 19 mm is the lateral bending. Since no weld condition presented nonconformities (discontinuities) in this type of folding procedures it could be considered as eligible for the tests of folding.

The condition G-1 showed highest variation in hardness with low microhardness at FZ (141.20 Hv). These results can be justified by a low dilution of the BM. The welded specimens under the conditions G-1 and G-2 showed greater variation in hardness, justified by highest heat input contributions, Tab. 10.

Table 10. Mean values of microhardness of the conditions.

Variation of hardness			
Condition G-1 (Region)	Condition G-2 (Region)	Condition G-3 (Region)	Condition G-4 (Region)
115.31 (FZ) –256.51(BM)	190.18 (FZ) – 266.78(BM)	202.15 (FZ) – 264.75(BM)	191.40 (WM) – 240.76 (BM)
141.20	76.60	62.60	49.30
Average heat input (kJ/mm)			
0.85	1.63	0.50	0.70

The behavior of micro-hardness can be seen in the curves of Fig. 5. All had similar behaviors, with a lower hardness at the center of welding increasing gradually toward the base metal and HAZ to stabilize after a given interval.

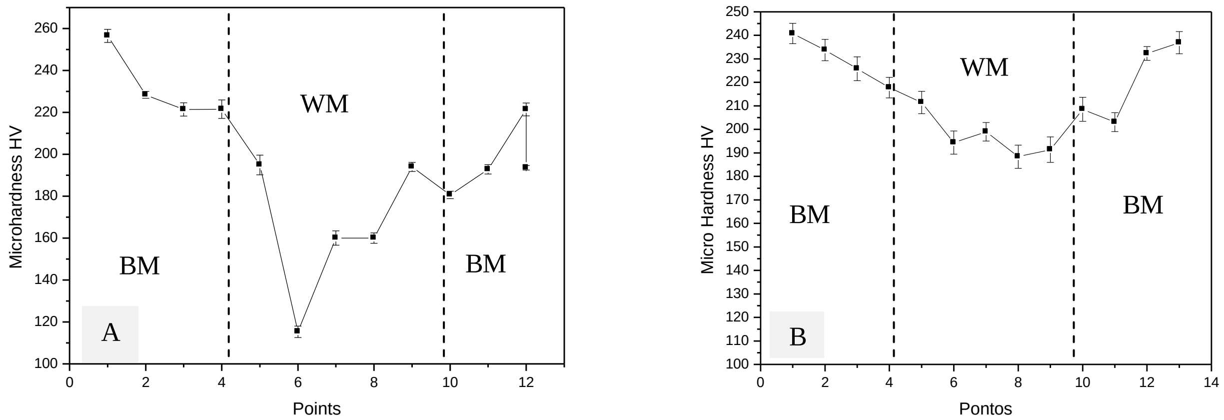

Figure 5. A) Microhardness profile of the condition G 1. B) Microhardness profile of the condition G 4.

The Charpy impact test, (paragraph 2.4) was carried out in specimens at temperatures of 0 º C and 25 º C (environment), and their average values are in Tab. 11.

Table 11. Average values of the Charpy V impact tests

Weld condition	Average heat input (kJ/mm)	Average Energy (J)			
		Welding metal (25°)	Welding metal (0°)	HAZ (25°)	HAZ (0°)
G-1	13.63	148.00	140.00	235.00	117.60
G-2	29.57	163.60	82.00	193.00	104.00
G-3	11.21	149.00	146.00	256.00	152.00
G-4	12.87	150.00	62.00	176.00	95.00

For all welding conditions, in general, it is observed that the impact energy in the weld metal is lower than in HAZs mainly because of the difference between grain size and in consequence mechanical properties.

4. CONCLUSIONS

The welding condition G-2 (35) demanded highest heat input average (1.63 kJ / mm), which has been justified by 7 welding passes at low speed. The variation of welding speed between the other conditions was not significant to justify substantial variations in the thermal contributions. These values were influenced by operational factors.

In general it was observed that the welding time was shorter for the conditions of lower angle (25 °), regardless of transfer mode.

The results of microhardness for each specimen showed basically the same behavior. The condition G-1 showed more variation (Tab. 10) in hardness (141.20 Hv), lowest hardness in the FZ, which could be explained by a low dilution of the BM. The conditions G - 3 and G - 4 showed less variation in hardness and highest hardness, justified by the increased intensity of plasticization in HAZ's with lesser width, in turn associated with lower angle of the bisel. In measurements of the extent of HAZ, the condition G-2 had the highest heat input per pass, justifying its greater width in relation to others.

In general, light microscopy for all conditions showed slightly enriched ferritic grains with pearlite in their contours. The SEM for all conditions showed, in general, the M-A microconstituents and retained austenite.

The FCAW-G process with two different geometries of joints with undermatched welding and variations of welding currents showed good performance of welds in regards to tensile and bending tests. These results were in line with the values for steel API 5L X80, according to API 5L, and AWS A5.20 (2005) of deposited metal. In view of this, all procedures can be considered as qualified, according to ASME Code - IX (2007).

For all welding conditions, in general, it is observed that the impact energy in the weld metal is lower than in HAZs because there is less grain size in these areas.

5. ACKNOWLEDGEMENTS

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