A STUDY ON HYDROGEN INDUCED CRACKING IN API STEEL WELD METAL USING THE MODIFIED G-BOP TEST

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Abstract. The improvement on composition and process of modern high strength low alloy steel (HSLA) practically eliminated the risk of occurring hydrogen induced cracking (HIC) on the heat affected zone (HAZ), however this phenomena has migrated to the weld metal (WM), thus the importance of research and study to avoid this phenomena to occur. From the several existing weldability tests used to appraise if the welded joints are subject to hydrogen induced cracking, the Gapped Bead-on-Plate (G-BOP) presents a great potential to evaluate hydrogen cracking on the weld metal. The main advantages of this test are the simplicity and assuredness on the quantification of the welding metal susceptibility to cracking and the application to determine minimum levels of preheating temperatures. The objective of this work was to evaluate the susceptibility to hydrogen cracking of the API X80 steel weld metal, welded with two different flux core wires at two different preheating temperatures, using the G-BOP test. A factorial planning was utilized to develop the experiment, the influence variables were the flux core wires type and the preheating temperature. The presence and rate of the cracks were analyzed as output variable. The results show that the API X80 steel weld metals executed with flux-cored electrodes are susceptible to hydrogen induced cracking when executed at room temperature and the preheating avoided hydrogen cracking.

Key words: G-BOP Test; Hydrogen Induced Cracking; Preheating

1. INTRODUCTION

The technology of pipeline welding (gas pipelines, oil pipelines, etc.) is in constant development, updated to comply with the weldability requirements of new materials and the ever-increasing necessities of productivity. Therefore, the study of new steel characteristics and welding metallurgy knowledge have become essential factors, they allow the development of compatible electrodes and adequate welding procedures.

The API X80 steel has been developed by the Brazilian industry as a high strength low alloy steel (HSLA), bainite with low carbon in laminated condition. Studies have been made to develop this type of steel as well as its weldability (Silveira and Silva&Carvalho, 2000). The Flux Cored Arc Welding (FCAW) process has proven to be a very promising alternative for welding steel pipeline, substituting the shielded metal arc welding (Mota, 1998). However, literature is very limited and few publications on the welding of this type of steel can be found.

Hydrogen induced cracking (HIC) has attracted more attention than any other phenomena in welding for the past years. Despite the wide range of studies on the subject, the formation of cracks induced by hydrogen in welded joints still defies welders and researchers. Hydrogen cracking happens at temperatures between -100 and 200^{o}C and it depends basically on three factors that are inter-related: quantity of diffused hydrogen on the weld, stress level on the material after the welding process and susceptible microstructure.

The ever-increasing interest on hydrogen induced cracking on the weld metal lead to the development of several tests including the G-BOP (Gapped Bead-on-Plate), developed in 1974 by Graville & McParlan (1974). The main advantages of this test are: low cost when compared to other methods, simplicity and assuredness on the quantification of the weld metal susceptibility to hydrogen cracking and the application do determine minimum levels of preheating temperatures. The method's main limitation is the thickness required for the test specimen which must be 50,8mm.

A factor that considerably influences the incidence of hydrogen induced cracking during the welding process is the preheating temperature. Preheating main function is to reduce the cooling rate consequently minimizing the formation of susceptible microstructures, accelerating hydrogen diffusion and diminishing residual stress caused by welding (Quesada & Zalazar, 2002).

The objective of this work is to evaluate the susceptibility to hydrogen induced cracking of the API X80 steel weld metals executed with two different flux cored electrodes. Another objective of this study is to observe the influence of the preheating temperature on the weld metals susceptibility to hydrogen induced cracking.

2. MATERIAL AND METHODS

The Base Metal used during the experiments was the API X80 steel. The material was received in the form of rings with the following dimensions: 762mm diameter and 15,8mm thickness. The chemical composition provided by the manufacturer and the equivalent carbon value (modified cracking parameter – Pcm) calculated according to the API 5L (2000) are shown on Table (1).

Table 1. API X80 steel chemical composition and modified cracking parameter (Pcm).

Chemical Composition (weight %)								
C	**Si**	**Mn**	**P**	**S**	**Al**	**Cu**	**Nb**	**V**
0,04	**0,17**	**1,75**	**0,019**	**0,004**	**0,032**	**0,01**	**0,073**	**0,005**
Ti	**Cr**	**Ni**	**Mo**	**N**	**B**	**Ca**	**Sb**	**CE (Pcm)**
0,013	**0,21**	**0,02**	**0,16**	**0,0035**	**0,0002**	**0,0014**	**0,01**	**0,156**

Two types of flux-cored electrodes were selected: the self-shielded type E71T8-K6, with a 1,7mm diameter and the gas-shielded type E71T-1, with a 1,6mm diameter. These flux-cored electrodes have their specifications based on the AWS A5.29 (1998) norm. The electrodes chemical composition provided by the manufacturer and the diffusible hydrogen content measured for the welding conditions used are presented on Table (2). The shielding gas used on the electrode type E71T-1 was CO_2 with a volumetric flow rate of 15 l/min, as recommended by the manufacturer.

Table 2. Electrodes chemical composition and diffusible hydrogen content (Hd).

Chemical Composition (weight %)									
flux cored electrodes	**C**	**Si**	**Mn**	**P**	**S**	**Ni**	**Al**	**Cr**	**H_D (mL/100g)**
E71T8-K6	**0,04**	**0,24**	**0,91**	**0,006**	**0,003**	**0,77**	**0,92**	**0,03**	**14,65**
E71T-1	**0,04**	**0,59**	**1,41**	**0,012**	**0,006**	**-**	**-**		**10,53**

The welds were executed at the welding laboratory at FEM/UNICAMP. For this process it was used a cell consisted of a micro processing, multiprocessing and synergic arc welding central "MTE Digitec 450/600" and a driving kart model 5302 BUG-O SYSTEM, to support and translate of the torch.

The nominal welding energy (Es) generated by the arc was used as a control parameter. The welding current and voltage were monitored by a computerized acquisition system consisted of an A/D board and the software Oscilos4. The nominal welding energy was calculated as a function of the current (I), the voltage (U) and the welding velocity (Vs) as shown on Equation (1).

$$Es = \frac{60 \cdot I \cdot U}{1000 \cdot Vs} \qquad (1)$$

The optimized welding parameters with constant nominal welding energy (2,000 J/mm) for the two types of electrode are shown in Table (3).

Table 3. Welding parameters for the two different electrodes.

Electrodes	**I (A)**	**U (V)**	**Va (m/min)**	**Vs (mm/s)**	**DBCP (mm)**	**Es kJ/mm**
E71T-1	**200**	**25**	**3,5**	**2,5**	**19**	**~2**
E71T8-K6	**220**	**22**	**3,5**	**2,5**	**25**	**~2**

The preheating was executed with an oxyacetylene flame. Monitoring and acquiring the welding thermal cycles was performed by a system consisting of a microcomputer, the software Aqdados from Lynx Technology, a A/D conversion board and a thermocouple "Type K" with a 1,6mm diameter. The temperature reading was done during the welding by immersing the thermocouple on the weld puddle.

A factorial planning (2^2) was used to develop the experiment. The influence variables were the type of electrode and the preheating temperature. Two preheating temperatures were used: environment temperature (between 25 and 28°C) and 100°C, according to Yurioca (2002). The response variable was the crack presence and the cracking rate on the weld metal. Five replicas for each condition resulted on a total of 10 tests. The adopted methodology to evaluate the obtained results consisted of an analysis of the variance with a level of error significance of 10%, which indicates an assurance of 90% (Montgomery, 1996).

Hydrogen induced cracking evaluated by the G-BOP test are quantified by the ratio between the cracked area (A_T) and the weld metal total area (transversal section) (A_{CS}), as shown on Equation (2). The aspect of a weld bead containing hydrogen cracking and tested with the G-BOP method is presented on Figure (1).

$$T_H = \frac{A_T}{A_{CS}} \cdot 100 \quad (2)$$

Where: T_H = Hydrogen Cracking (%);
A_T = Cracking Area (mm^2);
$A_{CS} = A_T + A_F$, Weld Bead Total Area (mm^2).

The cracking area and fracture area were measured using the image analyzer GLOBAL LAB-IMAGEM/2 and the Software AutoCAD 2000i.

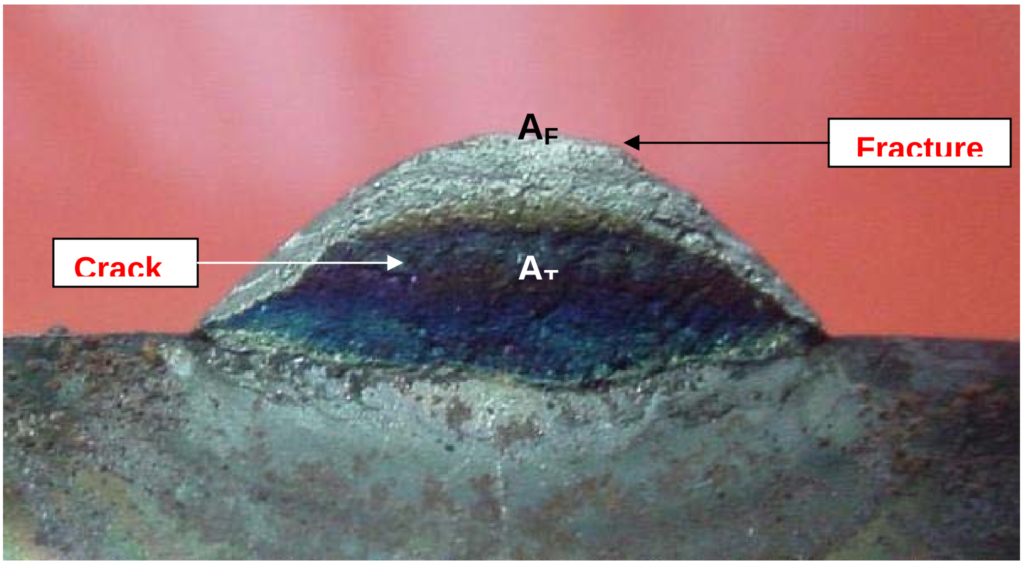


Figure 1. Representation of the corresponding regions for the hydrogen cracking area (A_T) and the fracture area (A_F)

3. RESULTS AND ANALYSIS

To evaluate the API X80 steel weld metal susceptibility to cracking a modified version of the G-BOP test was used (Silva, 2005). This version consists of substituting the solid blocks, normally used, by an assembly of blocks conjugating API X80 and ABNT 1020 steel plates. This composition makes the application of the G-BOP test on thin plates possible, minimizing its main limitation, which is the base metal thickness. The modified G-BOP test was applied on the account that the API steel used for this experiment had a 15,8mm thickness. Figure (2) presents a test specimens assembled for the modified G-BOP test as well as the weld bead deposited during the test.

After welding the test specimens, as shown on Figure (2), the test procedure was followed (Granville & McParlan, 1974). After the test the test specimens were opened and the weld bead transversal section was visually inspected. After identifying the presence of cracking the weld morphology was measured (height, width and transversal area) and the total cracking was calculated.

The obtained results for the hydrogen induced cracking (T_H) in all tested replicas, as a function of the type of flux cored electrodes and the preheating temperature used, are presented in Table (4). The table also presents the aleatory sequence used for the tests; the cracking area (A_T) and the weld bead transversal area (A_{CS}) that were used to calculate the hydrogen cracking percentage (T_H).

The results from Table (4) present a mean hydrogen cracking percentage of 61,5% with a standard deviation of 5,4% for the welds executed with the E71T-1 wire and a mean value of 70,8% with a standard deviation of 6,4% for the hydrogen cracking for the welds executed with the E71T8-K6 wire. In all replicas executed with a preheating temperature of 100°C no hydrogen cracking was observed (0%).

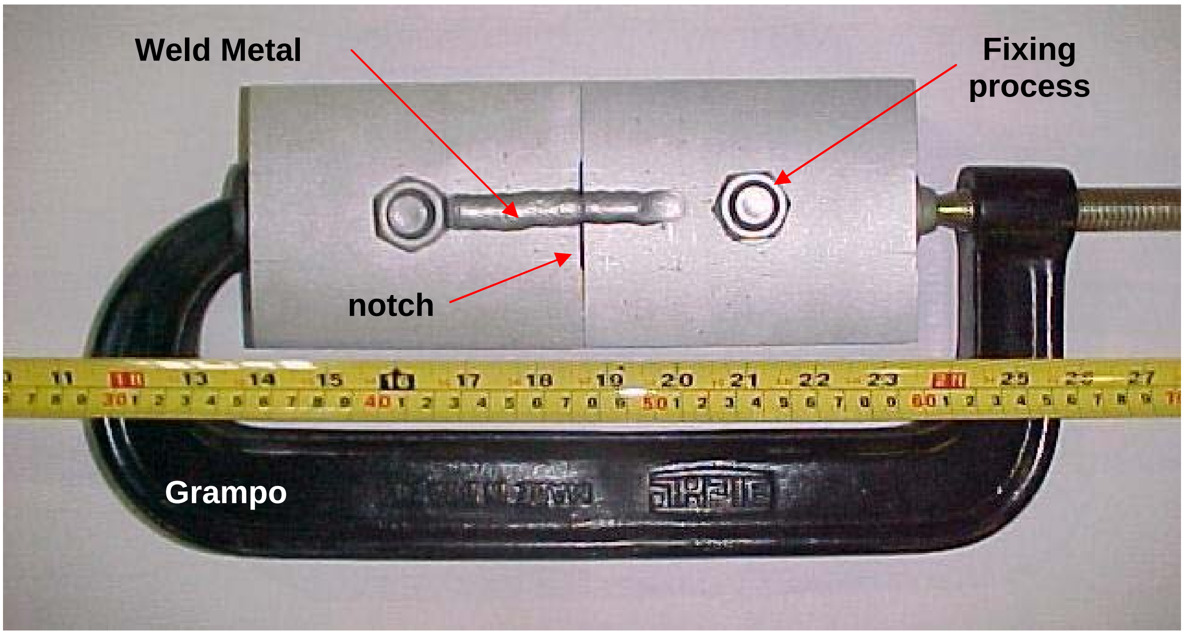


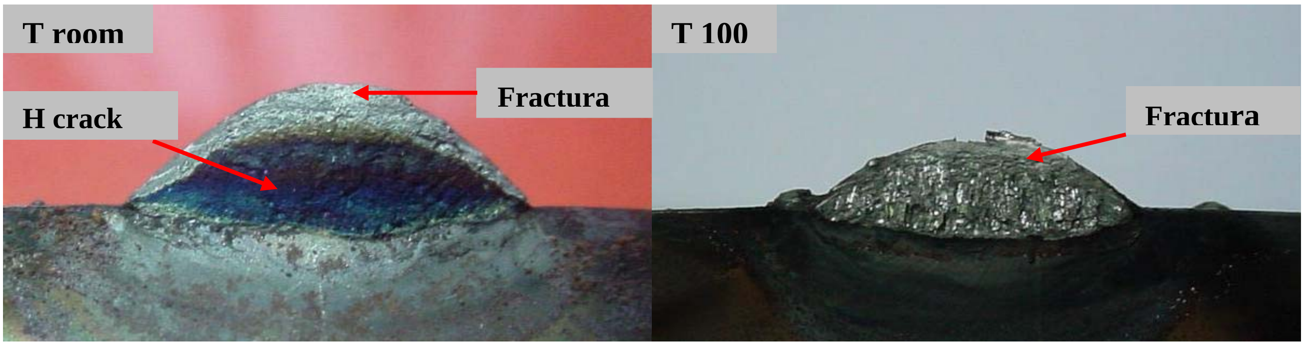
Figure 2. Tested specimen of the modified G-BOP test

Figure (3) shows a representative macrograph obtained during the tests. The weld metals at room temperature (Troom) presented hydrogen cracking (Figure 3a), independently of the type of flux-cored electrode used. In other words, only welds executed at ambient temperature presented two regions: an oxidized area, corresponding to the hydrogen cracking, and a fracture region, caused by a rupture occurred during the opening of the test specimen. Figure (3b) presents a representative weld metal fracture for the tests carried out with a preheating temperature of 100^oC, which did not occur cracking, independently of the type of electrode used. The samples executed with preheating presented only a fracture region, consequence of the rupture during the opening of the test specimens.

Table 4. Cracking percentage results for different electrodes and preheating temperatures.

Electrodes	Ambient Temperature				Preheating (100^oC)		
	Test Specimen	A_{CS} (mm^2)	A_T (mm^2)	T_H (%)	Test Specimen	Área CS (mm^2)	T_H (%)
E71T-1	01	41,5	26,4	63,8	11	44,8	0,0
	07	42,8	24,8	57,9	08	46,1	0,0
	03	41,5	24,5	59,1	04	46,6	0,0
	15	44,4	25,2	56,8	14	45,7	0,0
	17	42,9	29,9	69,8	18	45,5	0,0
E71T8-K6	05	50,5	39,8	78,8	12	54,9	0,0
	09	49,5	37,4	75,5	10	55,5	0,0
	13	50,7	33,3	65,7	20	54,9	0,0
	16	50,8	35,7	70,2	19	53,8	0,0
	02	50,2	32,0	63,8	06	55,3	0,0

A variance analyzis was done to compare the average T_H results of the diferents weld metals. The outcome of this estatistical analysis, presented on Figure (4), verify that the weld metal of the E71T8-K6 electrode (70,8%) was more susceptible to hydrogen cracking than the E71T-1 electrode (61,5%) when welded at room temperature. On the other hand both flux-cored electrodes weld metals presented the same behavior when welded with preheating, there was no cracking (T_H=0%).

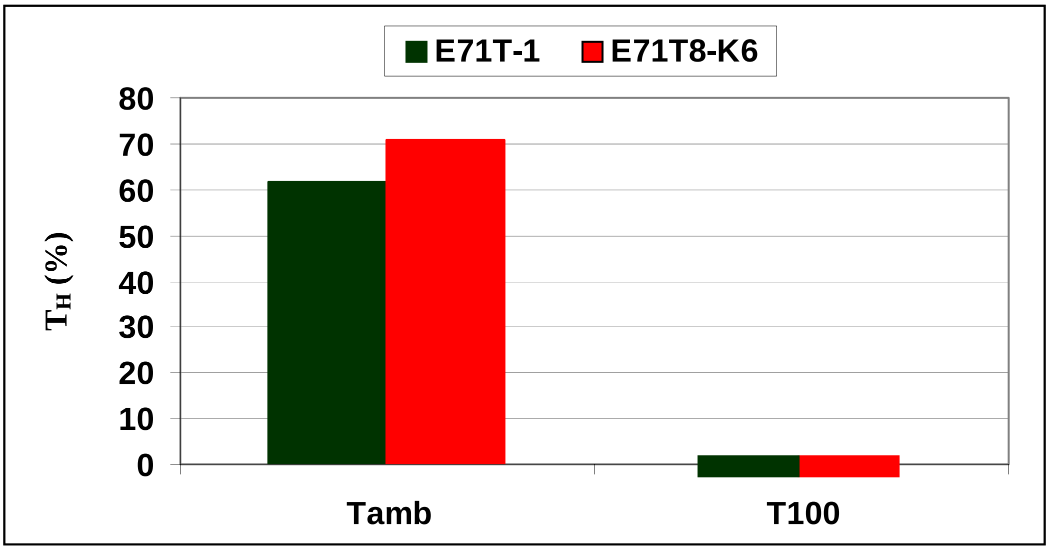


(a) (b)

Figure 3. Representative hydrogen cracking macrographs obtained during the modified G-BOP test.

As mentioned before, hydrogen induced cracking is an effect of three associated factors: susceptible microstructures, quantity of diffused hydrogen on the weld and the stress level on the material after the welding process. Attempting to explain the higher cracking concentration on the weld metal executed with the self-protected electrode (E71T8-K6) and based on the affirmative above, a comparative micrographic analysis was done between the different weld metals. However no significant difference was found on the microstructures. This is do to the chemical composition similarity between the electrodes and the API X80 steel and also to the welding conditions which were very similar.

Figure 4. Results of the weld metal hydrogen cracking as a function of the different flux cored electrodes and preheating temperatures used.



Another attempt to explain the higher cracking incidence on the weld metals executed with the E71T8-K6 electrode, a residual hydrogen analysis was done. The results, presented on Figure (5), were: for the E71T-1 electrode used at room temperature and preheated at 100^{o}C, 1,99 and 1,29 ppm of residual hydrogen was found, respectively; And for the E71T8-K6 electrode, 2,14 and 1,59 ppm for room temperature and preheated welding, respectively.

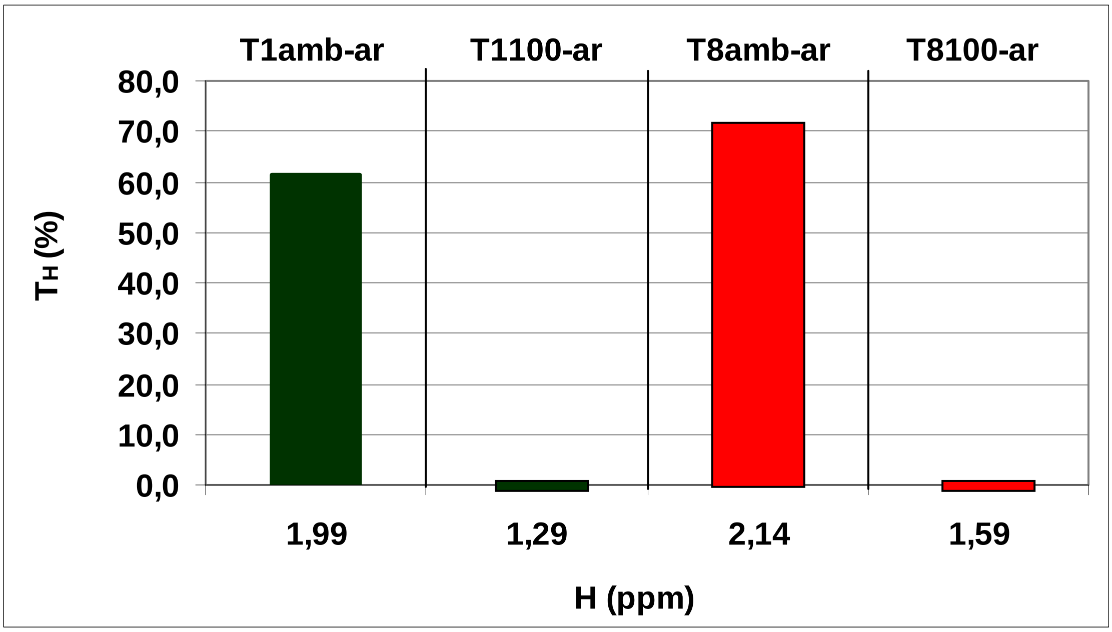


Figure 5 – Correlation between TIH and the content of residual hydrogen on the weld metals.

The results presented on Figure (5) indicate that the content of residual hydrogen on the weld metal executed with the E71T8-K6 electrode is higher that the content found on the weld metal executed with the E71T-1 electrode, independently of the preheating temperature.

As for residual stress, another important factor for generating hydrogen cracking, the fact that all tests were executed using the same amount of welding energy and the same procedure to perform the G-BOP test guarantied that the level of residual stress was the same in all cases.

Based on the above it is possible to affirm that the highest hydrogen content on the weld metal was found for the ones executed with the E71T8-K6 electrode. Therefore its higher susceptibility to cracking is do to the higher diffusible hydrogen content on this electrode.

The absence of cracking on the weld metals executed with the preheating temperature of 100^{o}C motivated a thorough analysis on the thermal cycle imposed to the weld during the welding process, with and without preheating.

Table (5) presents the peak temperature values (Tp), the time intervals (Δt_{8-5}) and the cooling rates (ΔT_{8-5}), between 800^{o}C and room temperature, as a consequence of the thermal cycles imposed to the API X80 steel weld metals executed with both flux cored electrodes.

It can be observed on Table (5) a higher peak temperature on the weld metals executed with preheating, independently of the electrode type used. This higher temperature peak is do to the increase on energy caused by the materials preheating before welding. It is also noticed on the table that the preheat imposed a lower cooling rate to the weld metal, in other words, the measured time interval for Δt_{8-5} was higher for the welds executed with preheating, independently of the flux cored electrodes used. This shows the influence that preheating has on the weld metal cooling.

Table 5. Peak temperature, time intervals and cooling rates imposed to the API X80 steel weld metals

Electrode	Room Temperature					Preheating at 100^{o}C				
	Tp (^{o}C)	Δt_{8-5} (s)		ΔT_{8-5} (^{o}C/s)		Tp (^{o}C)	Δt_{8-5} (s)		ΔT_{8-5} (^{o}C/s)	
E71T-1	1285	4,3		69,7		1342	15,9		18,9	
E71T8-K6	1315	4,6		65,2		1404	16,4		18,3	

Analyzing Table (5) and Figure (5) it is possible to observe that the steel preheating increased the cooling time Δt_{8-5}, which allows a greater interval for hydrogen diffusion; further on, the preheating reduces the temperature gradients of the set, consequently reducing residual stress. Both factors avoided hydrogen cracking on the API X80 steel weld metals.

4. CONCLUSIONS

From the obtained and analyzed results for the welding of API X80 steel with different flux cored electrodes at different preheating temperatures, it is possible to conclude that:

✓ The API X80 steel weld metal executed with self-protected flux cored electrodes type E71T8-K6 was shown to be more susceptible to hydrogen cracking than the gas-shielded flux cored electrode type E71T-1, welded at room temperature;

✓ The preheating at a temperature of 100°C strongly influenced the hydrogen cracking susceptibility of the welding metal avoiding the hydrogen cracking formation, independently of the electrode used;

✓ The modified G-BOP test induced crack formation, proving its efficiency while evaluating hydrogen cracking susceptibility of weld metals.

5. ACKNOWLEDGEMENTS

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