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CHARACTERIZATION OF WELDED JOINTS OF ASTM A-36 STEEL IN THE PRESENCE OF HYDROGEN

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Abstract. *In this work a study was conducted to evaluate the mechanical and microstructural behavior of welded joints in the presence of a source of hydrogen. Welded joints of ASTM A36 steel were obtained by GMAW and FCAW processes. Experimental development was carried out in totally random manner using a procedure known as factorial design (FD); were used as variables of influence the electrode wires ER70S-6 AWS and AWS E70C-6M and the shielding gas composition. In response variables were analyzed mechanical properties (mechanical strength and toughness), and the microstructure of the welded joints. The results were subjected to analysis of variance and validated for a 95% confidence. Analysis of the results showed that the absorption of hydrogen contained in the shielding gas does not influence the mechanical performance of the weld; however, it was found that hydrogen contained in the mixture changed static characteristics of the electric arc and consequently produced microstructural and fracture mechanisms changes, besides causing defects such as pores and bubbles.*

Keywords: *Welding; Hydrogen; Steel; Microstructure; Mechanical Properties.*

1. INTRODUCTION

Over the past decades, the search for productivity has challenged the industry to offer best quality products at the lowest value. In several cases, the welding processes represent much of a product manufacturing costs, and this justifies the continued efforts to seek improvements in this area.

The high-production welding processes such as GMAW (Gas Metal Arc Welding) and FCAW (Flux Cored Arc Welding), using shielding gas, currently has numerous applications in industry.

Shielded gases used in welding processes are extremely important, because in addition to protect the weld pool from contamination by atmospheric gases, have a significant influence on arc stability, the geometry of the weld bead, the metal properties welding and metal transfer mode to the weld pool (Teske and Martins, 2010). However, the shielded gas may be a source of contamination of the weld by hydrogen. In welding, three sources of hydrogen should be considered as key: welding consumables, moisture from the atmosphere and the base metal. Thus, any hydrogen is always present during the welding mechanical components.

The presence of hydrogen in the weld joint or even in steel can cause embrittlement of the material and even the phenomenon of hydrogen induced cracking (HIC) is a serious cause of failures in welded joints. The presence of hydrogen in steel may also produce a marked reduction of some of its mechanical properties. The reson why not to use shielding gases with hydrogen in its mix.

However, the hydrogen gas (H_2) mixed with the inert gas argon can be used in some cases such as those involving welding stainless steel and nickel alloys, because the mixture does not cause harmful metallurgical effect.

Durgutlu (2004), Gülença *et al*. (2005) and Huang (2010) conducted studies with mixtures of hydrogen and argon to verify the influence of hydrogen in static characteristics of the arc in macro-structural changes and mechanical properties of welded joints of stainless steel. The results showed that with increasing hydrogen content in the shielding gas was no significant change in static characteristics of the arc; the average size of grain of the weld metal increased, the amount of ferrite in the weld metal and decreases the toughness of the weld metal also decreased.

Another form of contamination of mechanical structures by hydrogen occurs when it is exposed to an environment rich in hydrogen. The presence of hydrogen can cause premature brittle fracture of steel under the action of a static loading. The loss of ductility caused by hydrogen has been verified in several studies on hydrogenation with steel, when compared to condition without hydrogen (Tiwari *et al*, 2009; Stroe, 2006).

Despite the importance of the subject and various studies, the existing literature still lacks information about the behavior of welded joints in the presence of an intense source of hydrogen, as well as the contamination of the joint by the hydrogen present in the environment when in operation.

With emphasis on the context presented, this work aims to evaluate the effect of contamination of welded joints by hydrogen presence in the shielding gas on mechanical and microstructural behavior; static characteristics of the electric arc welds and steel integrity ASTM A36 performed with the GMAW and FCAW processes.

2. MATERIALS AND METHODS

The base metal used was a steel ASTM A-36. It is a carbon structural steel of medium strength. Table 1 presents the main chemical elements in the chemical composition of the steel and its mechanical properties.

Table 1. Chemical composition and mechanical properties of steel ASTM A-36.

Chemical Composition (wt %)								
Fe	C	Si	Mn	P	S	Al	Cu	Nb
97.9	0.13	0.20	0.98	0.024	0.012	0.036	0.02	0.001
Mechanical properties								
Yield strength σ_y (MPa)			Tensile strength σ_t (MPa)			Elongation ε (%)		
312			447			27.5		

The weld metals used were two wires, a massive and another tubular type "Metal cored" with 1.2 mm diameter. The two wires are standardized by the AWS A5-18 as AWS ER70S-6 and AWS E70C-6M. The chemical composition of wires and mechanical properties were provided by the manufacturer and are presented in Tab. 2.

Table 2. Chemical composition and mechanical properties of the wires.

AWS ER70S-6						
Chemical composition			Mechanical properties			
C	Si	Mn	σ_y (MPa)	σ_t (MPa)	ε (%)	Charpy (J)
0.1	0.9	1.5	470	560	26	130 (20 ºC)
AWS E70C-6M						
Chemical composition			Mechanical properties			
C	Si	Mn	σ_y (MPa)	σ_t (MPa)	ε (%)	Charpy (J)
0.04	0.40	1.4	480	570	29	55 (-30 ºC)

For the shielding gas two mixtures were established, the first special containing in its composition 75% Ar (argon) + 25% CO_2 (carbon dioxide) and 70% Ar + 25% CO_2 + 5%H_2. The special blend with 5% H_2 in its composition was used to induce high hydrogen values during welding of the joint.

Statistical analysis of the results was performed by the method of analysis of variance, considering a significance level (α) equal to 5%. Therefore, the reliability of the results is 95%. Was performed according to the following structure: Factorial Design (FD) 2^2 - total of 4 tests per replicate, was two replicas, total 8 experiments. Influence variables were the two wires (ER70S-6 and E70C-6M) and the two shielding gas mixtures Already the response variables were the mechanical properties (tensile strength, yield strength and toughness), the microstructure and the integrity of the weld.

2.1. Welding Procedure

Have used for execution welding a source of microprocessor power, multi-threaded and synergistic. The welding was performed automatically, for both processes. A data acquisition system was used to control the variable and check the stability of the welding process.

The samples consisted of plates with dimensions of 12 mm x 62 mm x 115 mm. To carry out this work, a chamfer was machined "U" in the center of the plate and in the direction of lamination, with a width of 5 mm and a depth of 8 mm, to simulate the joining of plates. The plates were fixed with screws in a flat position on a steel support and level, as can be seen in Fig. 1.

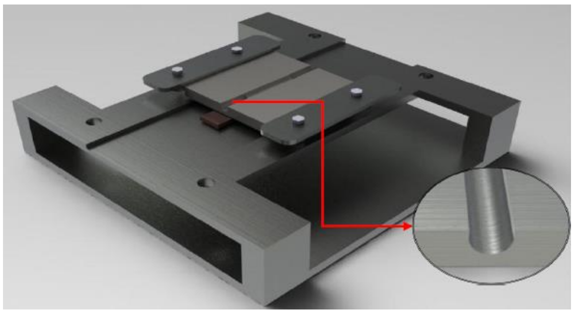

Figure 1. Schematic representation of the system used in the welding of test specimen.

2.2. Mechanical Testing

For the toughness tests to Charpy impact notch by the dimensions of the samples were defined according to ASTM E23 (1999). According to the norm the central slot line should be in the center of the weld for testing in the weld metal (WM); already in the heat affected zone (HAZ), the axis must intercept as much of the HAZ. In order to position the slot with greater safety in trials in HAZ and WM, the specimen of evidence were treated metallographic and attacked with Nital 2%. Figure 2 shows schematically the positions of notches in WM and HAZ. The Charpy tests were performed at room temperature in a machine Jb-W300 model semi-automatic.

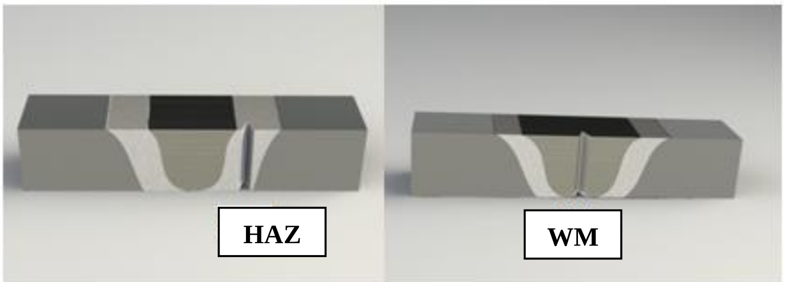

Figure 2. Schematic representation of the positioning of the notch according to ASTM E23 (1999).

In the tensile test we tried to get all the information and mechanical properties, that it can offer, the welded joint. Quantitative data on the mechanical features of the welded joint as ultimate strength (LR), yield strength (CO), total elongation (ε) and necking coefficient (φ) were analyzed. The dimensions, methods of implementation and specimens acceptance criteria were defined according to ASTM E8 / 8M-09.

Samples were taken from plates welded on the same plane, but perpendicular to the weld bead. The samples were cut in an EDM machine. Tensile tests were performed on a machine SERVO PULSER model, with capacity of 200 kN.

In order to observe the morphology, the microstructures the welded joint and the different modes or fracture mechanisms metallographic analyzes were performed on specimen of evidence tested. Optical microscopy (OM) was adopted as a technique for the identification of microstructures the welded joint. In a complementary manner, the scanning electron microscopy (SEM) was used to reveal microstructural details as well as for analysis and characterization of the different modes or fracture mechanisms observed in fractures of the specimens after the completion of Charpy tests.

3. RESULTS AND DISCUSSION

3.1. Welding of Test Specimen

A series of tests was performed by varying parameters: wire feed speed (wfs), arc voltage (U), welding speed (ws) and the stick out to be set energy appropriate welding and the respective welding parameters. The initial welding tests were carried out in ASTM A-36 steel plates in a flat position is then chamfered on plates with initial parameters of the wires according to the manufacturer's specifications. It was later performed an analysis of the morphology of the cord on the penetration, width and strengthening the weld bead for used wires and gases. The welding conditions selected and used in the experiments are shown in Tab. 3.

The welds were made with the torch held perpendicular to the test specimen plane. The bevels were soldiers in one pass, with reverse polarity (CC +).

Table 3. Welding parameters for different wires and shielding gases.

Shielding gas - 75%Ar + 25%CO_2						
Wire	I (A)	U (V)	wfs (m/min)	ws (mm/min)	Stick out (mm)	Es (kJ/mm)
ER70S-6	341,0	34,2	9,5	270	20	~2,6
E70C-6M	341,2	34,4	11	270	20	~2,6
Shielding gas - 70%Ar + 25%CO_2 + 5%+H_2						
Wire	I (A)	U (V)	wfs (m/min)	ws (mm/min)	DBCP (mm)	Es (kJ/mm)
ER70S-6	333,2	35	9,5	270	20	~2,6
E70C-6M	333,4	34,8	11	270	20	~2,6

Figure 4 shows graphs with the behavior of current versus time for the E70C-6M wire used when the different shielding gases.

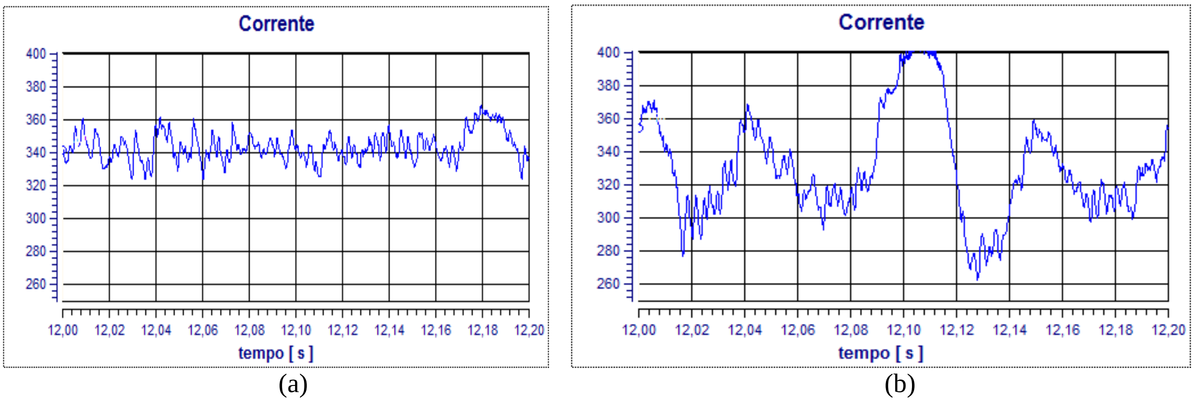

Figure 4. Current oscillograms for the E70C-6M wire (a) 75% Ar + 25% CO_2 and (b) 70% Ar + 25% CO_2 + 5% H_2.

The analysis of Tab. 3 shows the average value of the current has decreased when welding was carried out in the presence of hydrogen. This result is in agreement with that obtained by Tusek and Sudan (2000). The authors found that increasing the hydrogen content in the argon shielding gas resulted in a decrease in welding current for GTAW and GMAW processes, this because the hydrogen increases the electrical resistance of the arc and reduces the intensity of electric current. The decrease in the intensity of the current can also be justified by the high conductivity of hydrogen. According to Starling *et al*. (2011), high thermal conductivity gas should increase the resistivity of the arc, therefor the higher the resistivity of the electrical resistance larger arc. According Hooijmans (1994), the high thermal conductivity difference of hydrogen compared to other gases, causes major changes in static characteristics of the arc due to the greater energy dispensed per unit of time, then more energy is required to maintain a certain welding current.

The analysis of oscillograms shown in Fig. 4 show that hydrogen contained in the shielding gas influenced arc behavior and made the process more unstable. This increased instability of the process was observed in the study Tusek and Suban (2000), which stated that the presence of hydrogen in the shielding gas leaves the unstable welding process.

3.2. Tensile Test Results

Figure 5 shows a macrograph of a specimen after being subjected to tensile test. It can be observed the different regions of the welded joint (MB, WM and HAZ).

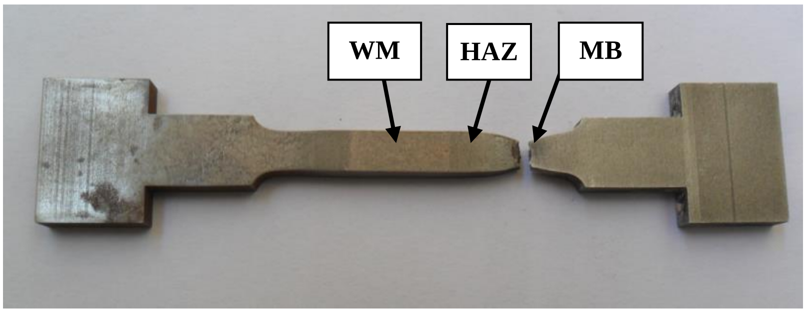

Figure 5. Macrograph of a specimen subjected to tensile test

All test specimens had the same behavior, namely the fracture always occurred in the base metal (BM). This behavior shows that the base metal has lower mechanical strength of the welded joint (WM and HAZ). By analyzing whether Tab. 1 and Tab. 2 shows that the two wires have used their mechanical properties of tensile strength and yield higher than the base metal being used in the condition known as overmatched. Table 4 shows the results of tensile tests for the specimens welded with ER70S-6-E70C-6M wires, and used shielded gas mixtures.

The ASTM standard specifies that for the A-36 steel endurance limit of the value is between 400 MPa to at least 550 MPa and at most; and the value of the yield strength is between 250 MPa to a minimum and 270 MPa maximum. The analysis of Tab. 4 shows that the values obtained are within established by the ASTM standard for A-36 steel. The tensile test proved the integrity of the weld, for all the specimens broke in the base metal, with maximum tensile stress above the minimum required by the standard. This behavior of the weld should be the use of filler metals with a higher mechanical strength than the base metal. It may also have contributed to this behavior, the fact that the handling of the samples welded for making the test specimen and all heat that focused on them in machining operations and time to perform the mechanical tests, contributed to the diffusion of hydrogen to the atmosphere.

Table 4. Yield strength results (σ_y), tensile strength (σ_t) and elongation

Shielding gas	Wire ER70S-6			Wire E70C-6M		
75%Ar + 25% CO_2	σ_E (MPa)	σ_R (MPa)	ε (%)	σ_E (MPa)	σ_R (MPa)	ε (%)
	347	484	57	340	496	62
75%Ar + 25% CO_2 + 5%H_2	σ_E (MPa)	σ_R (MPa)	ε (%)	σ_E (MPa)	σ_R (MPa)	ε (%)
	334	452	62	356	510	58

3.3. Results of the Toughness

Table 4 shows the energy absorbed values for Charpy impact tests of specimens taken from the welded joint for all tested conditions. The results presented in Tab. 4 are the mean of each replicate performed. The toughness of steel ASTM A-36 was also analyzed. 4 trials were carried out with test samples taken from base metal and yielded an average of absorbed energy of 171 J.

Table 4 - Absorbed energy (Joule - J) in the welded joint.

Shielding gas	Wire ER70S-6		E70C-6M	
	WM	HAZ	WM	HAZ
75%Ar + 25% CO_2	93	98	102	100
70%Ar + 25% CO_2 + 5%H_2	88	93	80	103

By analyzing the Tab. 4, it is observed that the base metal (171 J) always showed higher absorbed energy than the weld metal and the heat affected zone by heat, regardless of the type of wire and shielding gas. That the welded joint toughness behavior can be attributed to the type of filler metal, welding conditions used in obtaining the welded joint and the conditions under which the Charpy test. It is observed also in TAB. 4 that the HAZ tend to be tougher than the WM.

The higher tenacity values observed in the HAZ of the welded joints results differ from Qiu *et al*. (2000), the authors stated that the loss in joint toughness at HAZ most commonly occurs as a result of the welding-induced thermal cycle, which causes grain growth, adversely affecting the mechanical properties of the area, however, other authors as Batista *et al* . (2003) found similar results in high tenacity HAZ. They said that the greatest tenacity values obtained in the HAZ can be attributed to the action of thermal cycles experienced in BM during welding. Thus, the behavior of the welded joint toughness is fully dependent on the geometry, dimensions and basic metal type (composition, microstructure and mechanical properties); the type of filler materials (wire and shielding gas) and thermal cycle applied to the soldered joint.

3.3.1. Statistical analysis of the toughness of the weld

With the aim of improved reliability to the results obtained in the Charpy test, the same was analyzed statistically by analysis of variance. The results are considered a significance level (α) equal to 5%. Therefore, the reliability of the results is 95%.

The variance analysis was to calculate, from the results of the mean of the absorbed energy of the HAZ and WM, an F0 factor for each of the influence of variables as well as their interactions, and compare it to the corresponding value of the distribution F which is obtained depending on the adopted reliability of 95%, the error level of significance of 5%, the degree of freedom of the variance of factor analyzed and the degree of total variance of the results.

The results of the analysis of variance showed that the gas composition and the type of wire do not have any influence on the toughness of the HAZ and WM.

3.3.2. Analysis of the mechanisms of fracture

For a better analysis of the results of Charpy impact tests in WM, which showed a tendency to be more brittle when welded with hydrogen in the shielding gas composition, a study was conducted on the types of fracture mechanism observed. Fig. 6 and Fig. 7 shows the different mechanisms fractures.

The Figure 6 and Figure 7 shows the presence of mixed modes of fractures (dimples, cleavage and quasi-brittle) in a sample assayed by mixing 70% Ar + 25% CO_2 + 5% H_2, to the two wires used. The cleavage fracture micro mechanisms is the brittle behavior of the fracture, so it features the smallest impact energy that was absorbed by the specimen during the test, as in the case of trials in WM region, noted in Table 4. This result is in agreement with the literature, Miranda (1994) stated that the presence of hydrogen in the steel can switch the typical morphology of ductile fracture to essentially fragile. As the fractures with a mixture of 75% Ar + 25% CO_2 in CS, it appears that, for both wires used, fracture micro mechanisms was dimples representing a ductile fracture behavior, however with larger values energy absorbed.

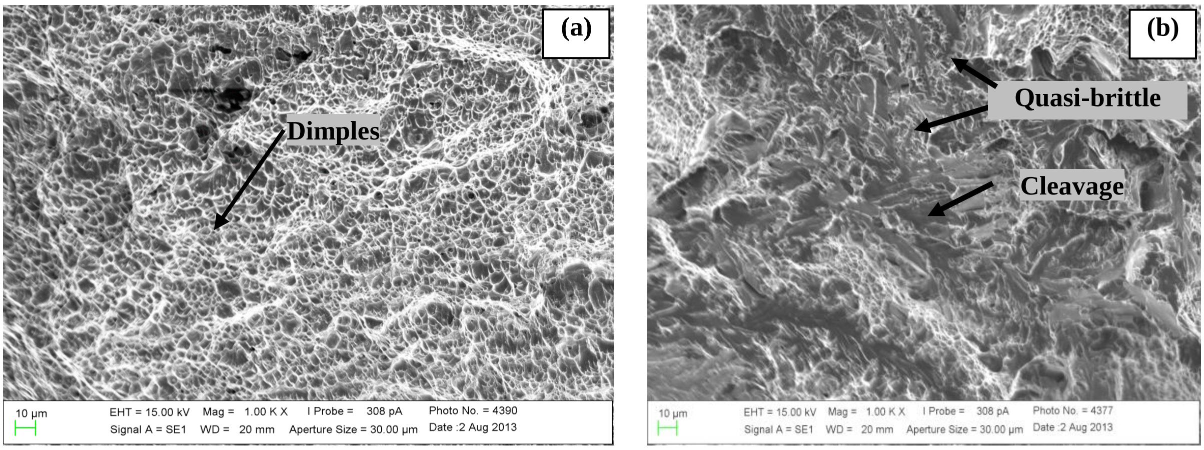

Figure 6. WM fracture Modes wire ER70S-6: a) 75% Ar + 25% CO_2; and (b) 75% Ar + 25% CO_2 + 5% H_2.

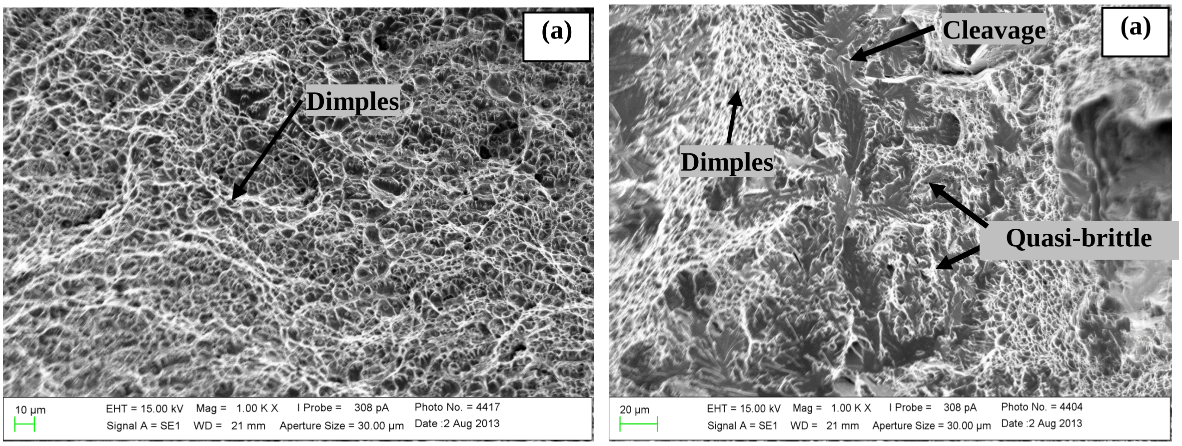

Figure 7. WM fracture modes E70C-6M wire: a) 75% Ar + 25% CO_2; and (b) 75% Ar + 25% CO_2 + 5% H_2.

3.4. Microstructural Analysis

The micrographs of Fig. 8 were obtained in the center of the welded joint weld metal with the ER 70S-6 wire. It can be seen that besides the microstructure pearlite, the microstructures have WM: grain boundary ferrite (PF (L), Widmanstätten ferrite (WF), polygonal ferrite (PF) and acicular ferrite (AF).

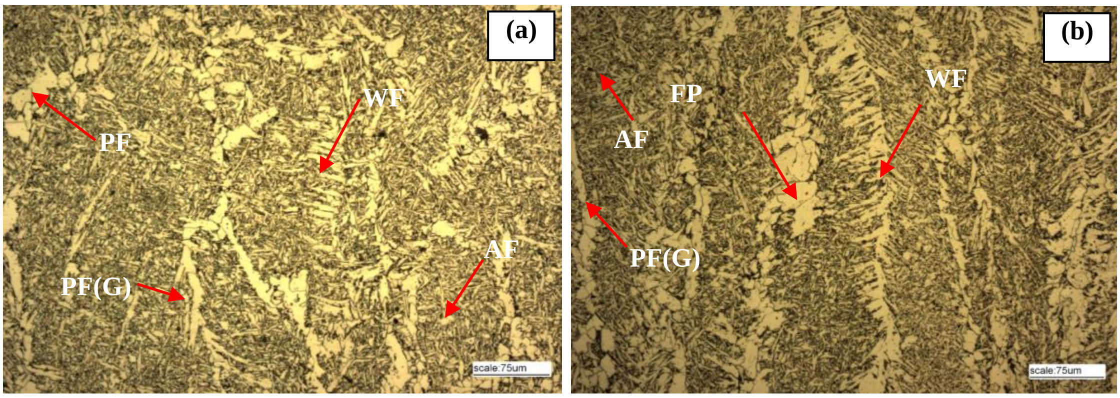

Figure 8. WM Optical Micrograph wire to the ER 70S-6: (a) 75% Ar + 25% CO_2) and (b) 70% Ar + 25% CO_2 + 5% H_2.

Analysis of Fig. 8 shows that WM run without hydrogen in the gas has a greater amount of AF, since the WM resulting in the presence of hydrogen gas consists of larger columnar grains, smaller and larger amounts of AF, WF, this composition microstructure contributes to lower toughness of the weld metal.

The acicular ferrite is a constituent which is in the form of fine ferrite grains not parallel, nucleando-up inside the grain of austenite. The microstructure of acicular ferrite has the potential to combine high strength and toughness; it appears disorganized, making it difficult to crack propagation. This is in accordance with the results of impact seen in Tab.4 where you can observe higher absorbed energy values in the samples welded with 75% Ar + 25% CO_2.

Gülença *et al.* (2005) stated that the grain size increases when using a mixture of argon with hydrogen compared to pure argon for the same conditions. This is due to the dissociation of hydrogen molecules in electric arc releasing more heat when compared to other gases used in welding. Thus the entry of more heat in the joint causes a slower cooling, resulting in higher grain sizes.

Figure 9 shows micrographs of the welded joint WM with the E70C-6M wire. It can be seen that the WM obtained by mixing 75% Ar + 25% CO_2 shows microstructure perlite beyond the microstructures: grain boundary ferrite, polygonal ferrite and acicular ferrite. But the resulting mixture WM of 70% Ar + 25% CO_2 + 5% H_2, has besides the mentioned microstructures, the ferrite Widmanstätten.

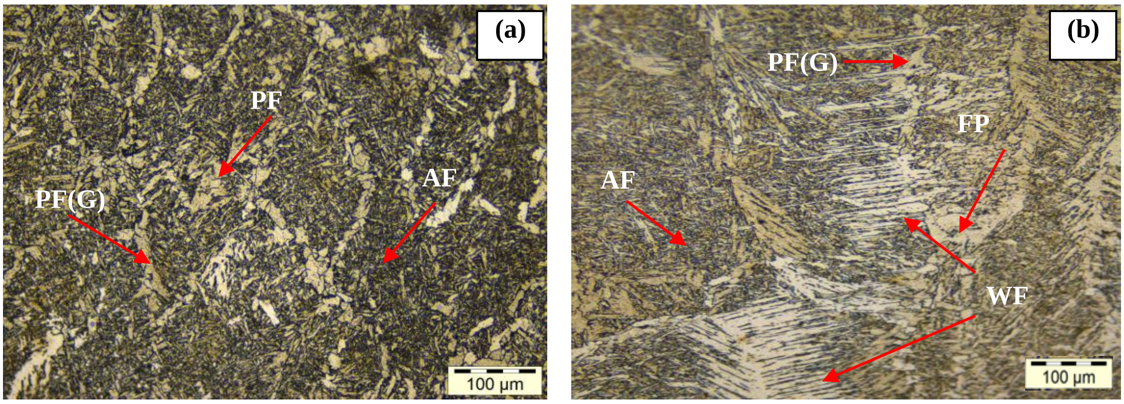

Figure 9. Optical Micrograph WM for the E70C-6M wire (a) 75% Ar + 25% CO_2 and (b) 70% Ar + 25% CO_2 + 5% H_2

The analysis of FIG. 9 shows that the amount of FA is the lowest WM admixture with hydrogen. There is also a very significant presence of WF and coarser grain. This is because the hydrogen causes a higher heat input in the molten area, favoring the formation of such microstructure, since this type ferrite will form if higher processing temperatures and is favored by slow cooling.

3.5. Welded Joint Integrity

All welds performed with a mixture 70% Ar + 25% CO_2 + 5% H_2, exhibited bubble formation in the weld metal. Already in welds performed with the mixture 70% Ar + 25% CO_2 bubbles and pores were observed. Figure 10 shows the bubbles observed in the weld bead to the solid wire ER70S-6 and tubular wire E70C-6M.

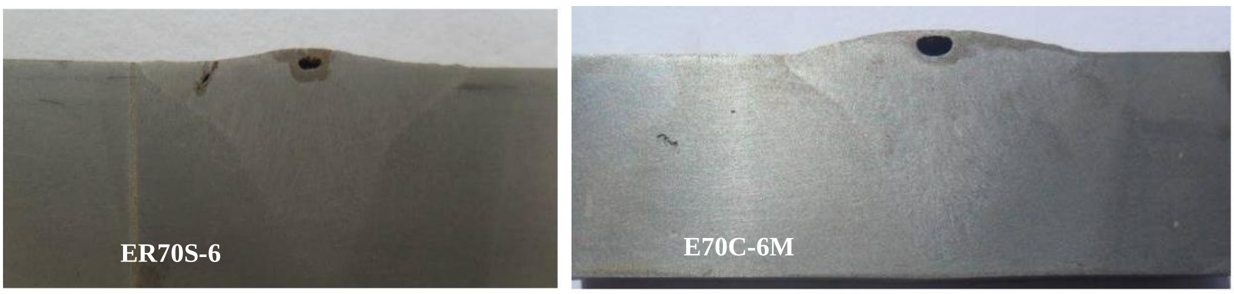

Figure 10 - bubbles caused by the presence of hydrogen in the shielding gas.

According Hooijmans (1994), the formation of pores and bubbles welded joints occurs when the concentration of gases dissolved in the molten metal exceeds the solubility of the material or even when the bubbles are produced in the solidification front, being the gas solubility of the metal much less solid than in the melt. According Hooijmans (1994), the tendency to form porosity is dependent on the material, the amount of hydrogen present at the time of welding and also the experimental conditions, in particular the rate of solidification.

4. CONCLUSIONS

Based on the proposed objectives, the experimental methodology used and the results obtained and discussed in this research, some conclusions can be assumed.

- All the samples in the tensile test had the same behavior, so the fracture always occurred in the base metal regardless of the type of wire and used shielded gas.
- The absorption of hydrogen contained in the shielding gas did not influence the mechanical behavior of welded joint.
- The weld showed lower toughness than the base metal.
- Statistical analysis with an error of significance level of 5%, indicating a reliability of 95% in results; it showed that the variables of influence did not affect the mechanical behavior of the welded joint.
- The use of hydrogen in the shield gas increased the electrical resistance decreasing arc current intensity used for both wires.
- The use of hydrogen in the shielding gas produced microstructural changes and fracture mechanisms in WM and cause defects such as pores and bubbles.

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