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## ANALYSIS OF THE MECHANICAL BEHAVIOR IN THE INTERFACE OF THE BUTTERING WELD OF STEEL AISI 4130 WITH INCONEL 625

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**Abstract.** *The main objective of this work was to analyze the mechanical behavior of the buttering weld of the AISI 4130 steel with the nickel alloy 625. The interface of the buttering with the base metal has been shown to be fragile to the hydrogen from cathodic protection. Several researches have been developed, however few have dealt with the welding procedure. Randomized design by levels in experimental development was adopted. As factor of influence the conventional and pulsed welding current modes were analyzed. The response variables were the dilution of the base metal, the microstructure and the mechanical properties at the interface between the buttery and the base metal. The results showed that the conventional current mode presents a more unstable arc, consequently the presence of splash was observed, whereas in the pulsed current mode, a stable arc was observed without splash. The microstructural analysis also showed that the buttering performed with pulsed current has lower levels of dilution than the conventional current mode. In addition, it was verified that the interface of the buttery with pulsed current mode, promoted greater control of partially diluted zones, minimizing the formation of fragile zones, resulting in a joint with greater mechanical resistance.*

**Keywords:** *welding, buttering, nickel alloy, mechanical properties.*

### 1. INTRODUCTION

In the Oil and Gas industry, high strength steel components are used to manufacture underwater equipment, which must meet the strict demands required for a good application in extremely aggressive environments, due to the high pressures existing in such a highly corrosive location.

When subjected to corrosion conditions, these components are generally internally coated by welding with the Inconel 625 nickel alloy and are heat treated after welding to meet the hardness standard recommended by NACE MR0175 / ISO 15156 (Ferreira, 2014). According to Ferreira (2014), the post-weld heat treatment (PWHT) for the welding between the assembling and the adjacent pipe, usually of microliged steel (X65 or X70), due to the complex piping layout distortions. Therefore, special welding procedures are used for this sealing weld. Pre-welding of the floor slabs and post-weld heat treatment in the factory is carried out previously. The buttering should be so thick as to keep the HAZ of the closing welding sufficiently far away from the low alloy steel, ensuring the fixed hardness standard, and this way, preventing the joint from requiring further heat treatment.

As the buttering accommodates the Heat Affected Zone (HAZ) of the closing weld, it is possible to meet the established hardness standard. Traditionally, this buttering and sealing welding are performed with nickel alloy 625 to ensure compatibility with the inner layer, Fig. 1 (b).

Despite having several years of successful use, dissimilar welded joints in manifolds, showed failure in the buttering interface of the 8630M steel previously buttered with Inconel 625 subjected to cathodic protection, Fig. 1 (a). Catastrophic failures occurred in the North Sea and Gulf of Mexico. In view of this problem, investigations were carried

out in the Gulf of Mexico through hydrostatic tests, and the presence of circumferential crack at the buttering interfaces was observed (Stroe, 2006; Milititsky et al., 2010).

The melting line generated in these dissimilar joints, often referred to as the most critical region and the large amount of atomic hydrogen adsorbed on the joint surface, were pointed out as the probable cause of the flaws found in these joint types. In this context, this work aims to evaluate the behavior of two welding procedures that used pulsed and conventional chains on the mechanical properties of buttering joints of AISI 4130 steel with Inconel 625.

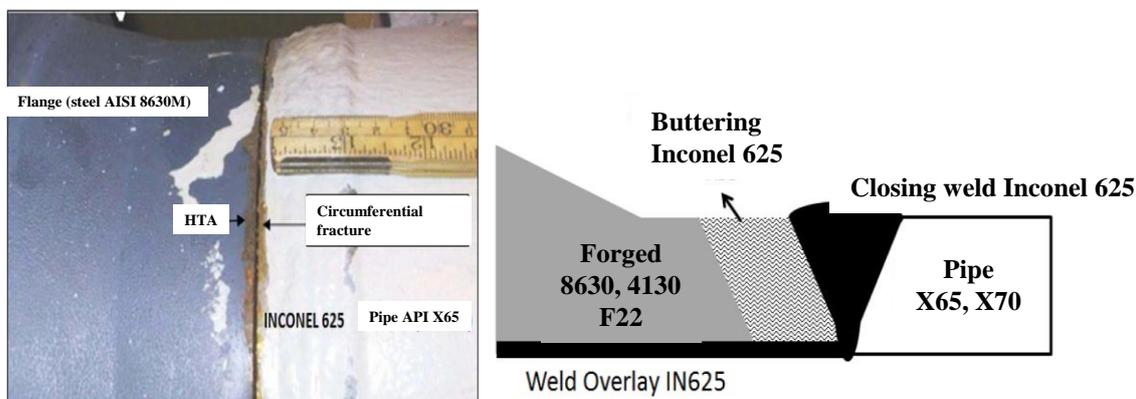


Figure 1. a) Representation of a dissimilar AISI 8630 / Inconel625 solder in the manifolds. b) Failures in offshore installations in the AISI 8630M / Inconel 625 steel flanges (Grittos, 2008)

## 2. EXPERIMENTAL PROCEDURE

AISI 4130 steel was used as support metal; its chemical composition is shown in Table 1. It is a high strength and low alloy steel, widely used in the oil and gas segment, because it meets the high mechanical resistance standards required for this type of application.

Table 1. Chemical composition of AISI 4130 steel

Composition	C	Mn	P	V	Ni	Si	Cr	Mo
AISI 4130	0,30	0,53	0,011	0.01	0,07	0,26	0,89	0,17

To meet the application requirements of NACE MR0175 regulation, before the buttery welding, the steel went through the tempering and heat treatments. The criterions used to perform the heat treatments are shown in Fig. 2.

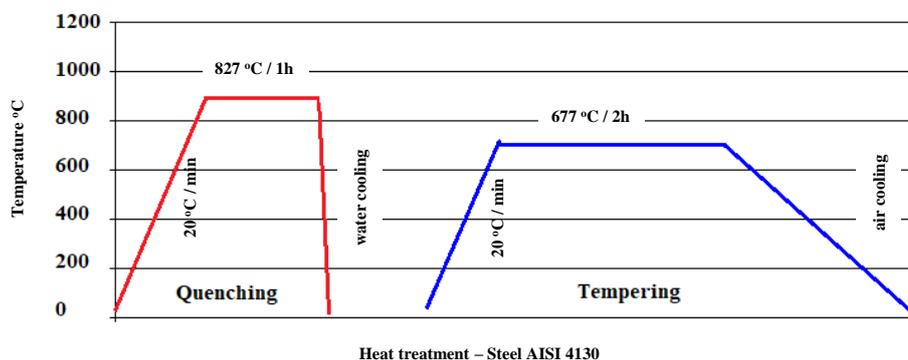


Figure 2. Heat treatment of steel AISI 4130

The AWS ERNiCrMo-3 wire (Inconel 625), with a diameter of 1.2 mm, was used as the addition metal. The wire is a nickel alloy with high resistance to corrosion and mechanics and is therefore used in the oil and gas segment as a coating metal and join for welding components and structures. Another important application is its use as butyl metal in flange composite joints and components of dissimilar mechanical systems. The chemical composition, in terms of weight percent are shown in Table 2.

The GMAW (Gas Metal Arc Welding) welding process was used. The shielding gas used was a mixture of inert gases (75% Air / 25% He), with a flow rate of 20 l / min. In welding both the butting and the filling a welding cell composed of a 32-bits / 450-A DIGI Plus A7-ARM7 type welding source was used for welding on both the buttering and the filling of the joints; a steel bench; a mechanical device for linear movement of the torch with regulation of both height and positioning in relation to the welding direction and a system for monitoring and acquiring current and voltage signals.

Table 2. Chemical composition of INCONEL 625 (% mass) according to manufacturer

Ni	Cr	Mo	Fe	Nb	Ti	Al	C	P	Mn	S	Si	Cu	Co
64,5	22,27	8,87	0,13	3,59	0,20	0,3	0,02	0,003	0,01	0,001	0,05	0,01	0,01

The experimental procedure used in the development of this research is shown in Fig.3.

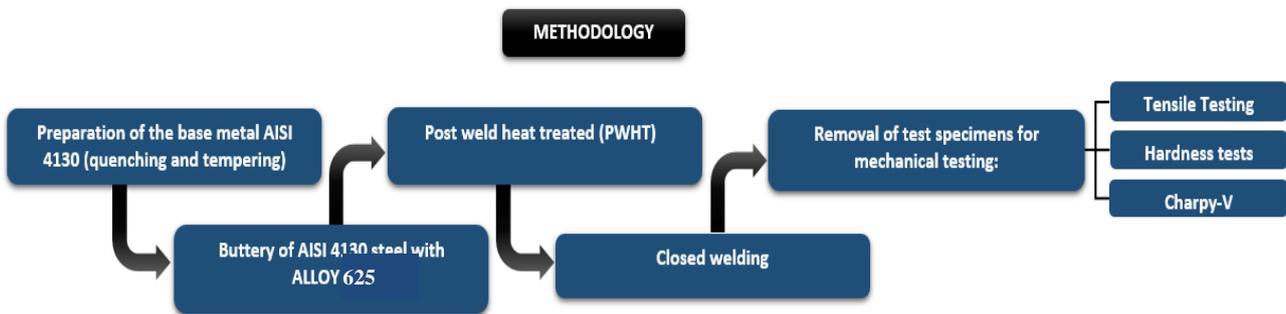


Figure 3. Flowchart of the experimental procedure

The base metal was preheated prior to the buttering, from at least 240 ° C. At the same time, the interpass temperature was maintained in the range of 240 ° C to 280 ° C. The welding values used for the buttering are shown in Table 3.

Table 3. Welding parameters for different welding procedures

MIG conventional							
Wire	Welding current (A)	Voltage (V)	Welding speed (mm/min)	Welding energy (kJ/mm)			
Alloy 625	183.9	32.2	164	2.16			
MIG pulsed							
Wire	Welding Current (A)	Voltage (V)	Ip (A)	Ib (A)	Tp (ms)	Tb (ms)	Welding energy (kJ/mm)
Alloy 625	187.7	36.4	300	131	3	5.1	2.49

After the setting of the welding bases, the buttering was performed. Fig. 4 shows the amount of strands and layers applied in the buttering. The number of layers was set to ensure a minimum of 9.5 mm thickness on the base metal after machining.

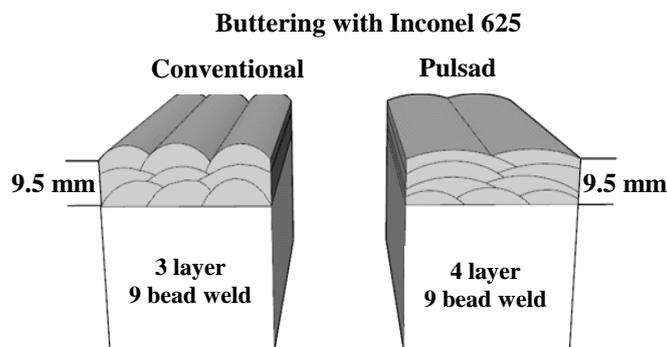


Figure 4. Layers and bead weld used in buttering welding

After welding, the samples were subjected to a heat stress relief treatment (TTAT), which consisted of a heating at the rate of 20°C / min. to the temperature of 677 ° C, maintained at this temperature for two hours, After that cooled by fresh air. The metallurgical characterization of these brazing welds was performed by Beltrão et al. (2017).

After the TTAT, the samples and sheets of ASTM A36 steel were machined to form the joint for the closing weld. Figure 5 shows the gasket prepared for welding; the dimensions of the samples make part of the weld joint, the "J" machined bevel, are shown in the figure. After welding the welded joint did not receive any heat treatment after welding.

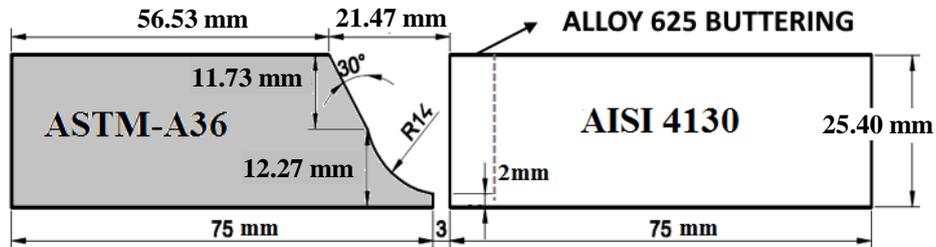


Figure 5. Joint to closed welding of the ASTM-A36 steel and AISI4130 bettered steel

The welding sealing of the joint using the welding parameters shown in Table 4.

Table 4. Welding parameters for weld joint with INCONEL 625 in conventional and pulsed modes

Joint welding using INCONEL 625		
Welding current mode	Conventional	Pulsed
Average gas flow (m <sup>3</sup> /min)	20	20
Average current (A)	183,9	187,7
Medium voltage (V)	25	36,4
Welding speed (mm/min)_Wire feed speed	180	200
Wire feed speed (m/min)	6,5	6,5
DBCP - Contacto tip distance - Sample (mm)	14	17

The samples were prepared for the Charpy test, according to the Standard (ASTM E23-02, 2012) using 10x10x55mm dimensions, with a notch in V-shaped. The tests were carried out at room temperature, 2 samples were drawn for Charpy-V Impact test on the weld metal and 2 samples for the Charpy-V Impact test in the ZAC-GG, as shown in Fig. 6.

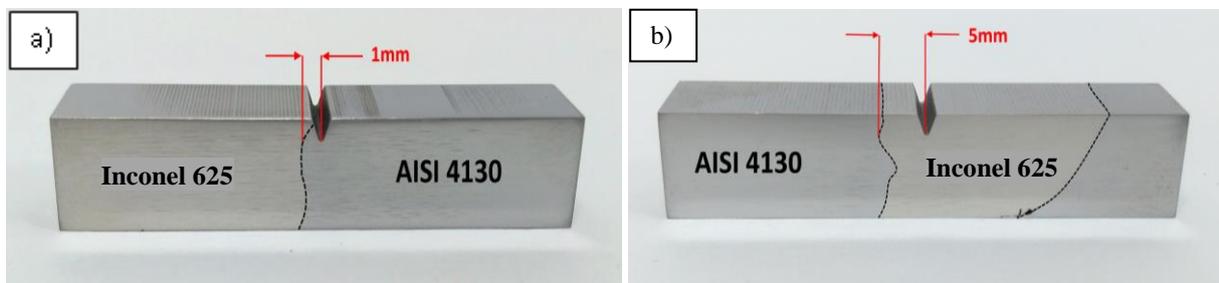


Figure 6. Test specimens for charpy assays: a) notch near the melting line, b) notch in the weld metal

In order to evaluate the mechanical strength of the welded joints tensile, tests were carried out. The tests were performed according to ASTM E8 / 8M-04, 2009. For this test, 3 different samples were extracted for each welding condition performed as shown in Fig. 7.

The tensile tests were performed using a Shimatzu servo controlled universal test machine, with a maximum capacity of 200 kN and a displacement rate control of 0.6 mm / min at room temperature, determining the limit of flow from the 0.2% permanent deformation, and the tensile strength limit, from the maximum load supported by the component.

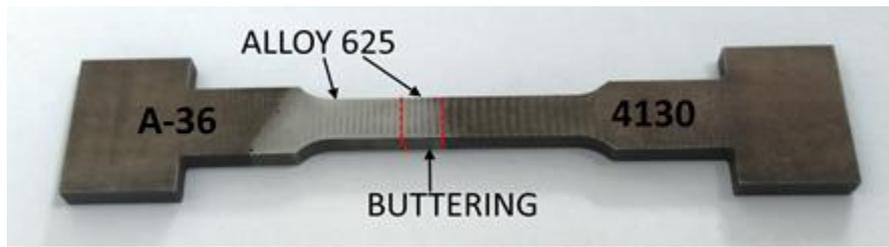


Figure 7. Test specimen for the tensile test

The hardness tests followed the technical requirements specified by the NACE MR0175 standard, evaluating the AISI4130 buttering steel with INCONEL 625 in the dissimilar welded joint. For the evaluation, the determination of the hardness in the area of the buttering in the transverse plan of the welding was shown as in Fig. 8.

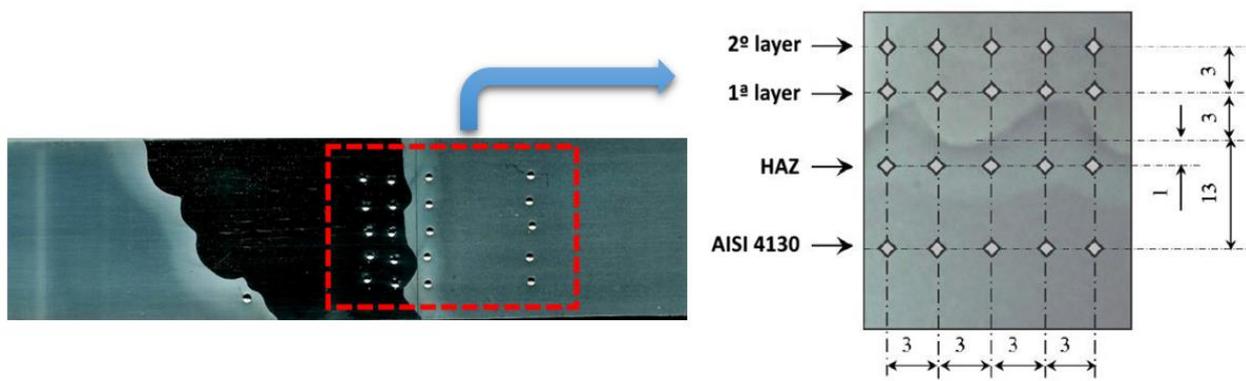


Figure 8. Location of weld joint hardness measurements in the transversal plan (measured in mm)

### 3. RESULTS AND DISCUSSIONS

#### 3. 1. Oscillograms Current vs. Time

Figures 9 and 10 show the welding current oscillograms x time for the buttering welds for Inconel 625 in the pulsed and conventional current modes, respectively.

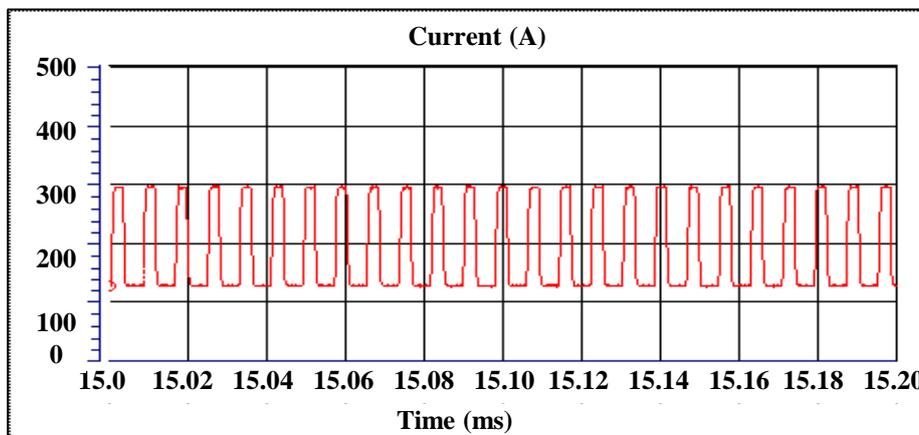


Figure 9. Current oscillogram for buttering welding with Inconel 625 and pulsed current

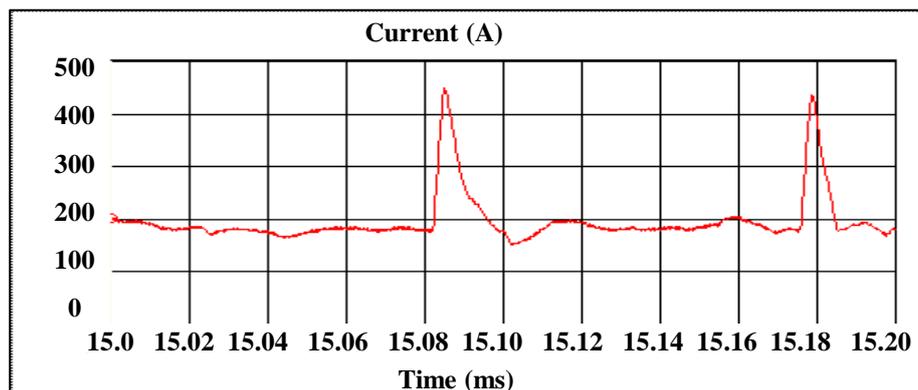


Figure 10. Current oscillogram for butt welding with Inconel 625 and conventional current

The analysis of Figure 9 shows a mode transferring characteristic of an oscillogram of current controlled by pulsation. During the buttering welding the electric arc remained stable, ensuring a total absence of spatter. Figure 10 shows an oscillogram that characterizes the mode of globular metal transfer. During the welding of buttering, it was possible to observe a certain degree of instability of the electric arc, providing a great amount of spatter.

### 3.2. Tensile test

The tensile tests were developed with the purpose of obtaining data that allowed analyze the influence of the current mode on the welded joint behavior when subjected to the tensile stress. The mechanical behavior of the welded joint was evaluated through the parameters: tensile strength limit, flow limit, stretching and stress.

For the tensile test, three specimens were used for each current mode condition (conventional and pulsed). The test specimens after the tests are shown fractured in Fig. 11, where it can be observed that all the fractures occurred in the base metal, which proves the integrity of the welded joint, for both conditions, demonstrating that the welded joint presents a good mechanical integrity.

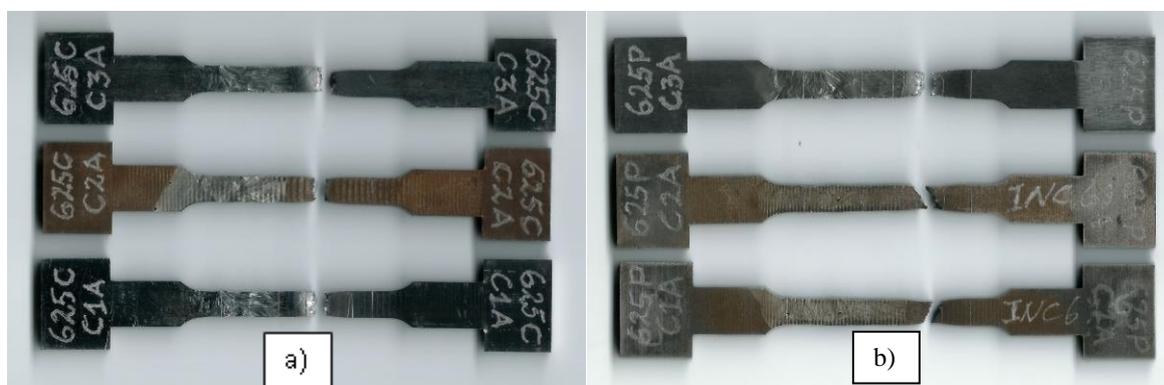


Figure 11. Samples tested: a) Welded with conventional current and b) Welded with pulsed current

### 3.3. Charpy Testing

In this section we present the results obtained in the impact tests performed with notched samples in the welded metal and the HAZ area. The grooves were placed in the area of HAZ-GG once that in this area the temperature variations during the welding have a greater potential to affect the tenacity of the material. This criterion was used for the two levels of welding energy, from the conventional and pulsed current modes, in order to compare their effect on toughness of the impact.

The Charpy test results are shown in Table 5. The results show that the impact strength of the weld metal is higher than in the HAZ area, regardless of the welding current mode used. The results also show that the welder metal performed with the pulsed current mode is harder than the welder metal obtained with the conventional current mode. These lower values of tenacity observed in the HAZ of the welded joints are in agreement with the results verified in some studies (Qiu et al., 2000; Fairchild et al., 1991), that assures that the loss in the tenacity of the joint happens more commonly in the HAZ, as a result of the welding-induced heat cycle, which causes grain growth, adversely affecting the mechanical properties of this area. (Cantarin, 2011) attributes the fall in impact resistance to microstructural changes in

the HAZ. Two phenomes must be observed. The first is the reversion of the coarse martensitic phase to the refined martensitic, which can increase the impact resistance. The second is the formation of fragile phases that may have occurred in this area due to the heat input.

Table 5. Results of the Charpy impact test

		Test 1 (J)	Test 2 (J)	Mean
Inconel 625 Conventional	Interface	50.0	50.0	<b>50.0</b>
	Weld metal	87.0	138.0	<b>112.5</b>
Inconel 625 Pulsed	Interface	54.0	60.0	<b>57.0</b>
	Weld metal	146.0	186.0	<b>166.0</b>

The results also showed that the welding energy variation used in this work was not significant in the influence of the impact of this material on the HAZ of the dissimilar joint, in the welding metal there was a greater dispersion of the absolved energies, where for a higher welding energy of the process, a higher impact toughness value occurred.

The absorbed energies of all test samples were above that required by API 6A, which establishes the minimum value of 20 J, therefore, all the heat cycles employed presented satisfactory results that allowed the approval of the impact resistance. The values given in this test indicate that the welding deposited coating has adequate toughness for use in the oil and gas segment.

Figure 11 shows the macrographs of the fractured faces of the samples and their respective values.

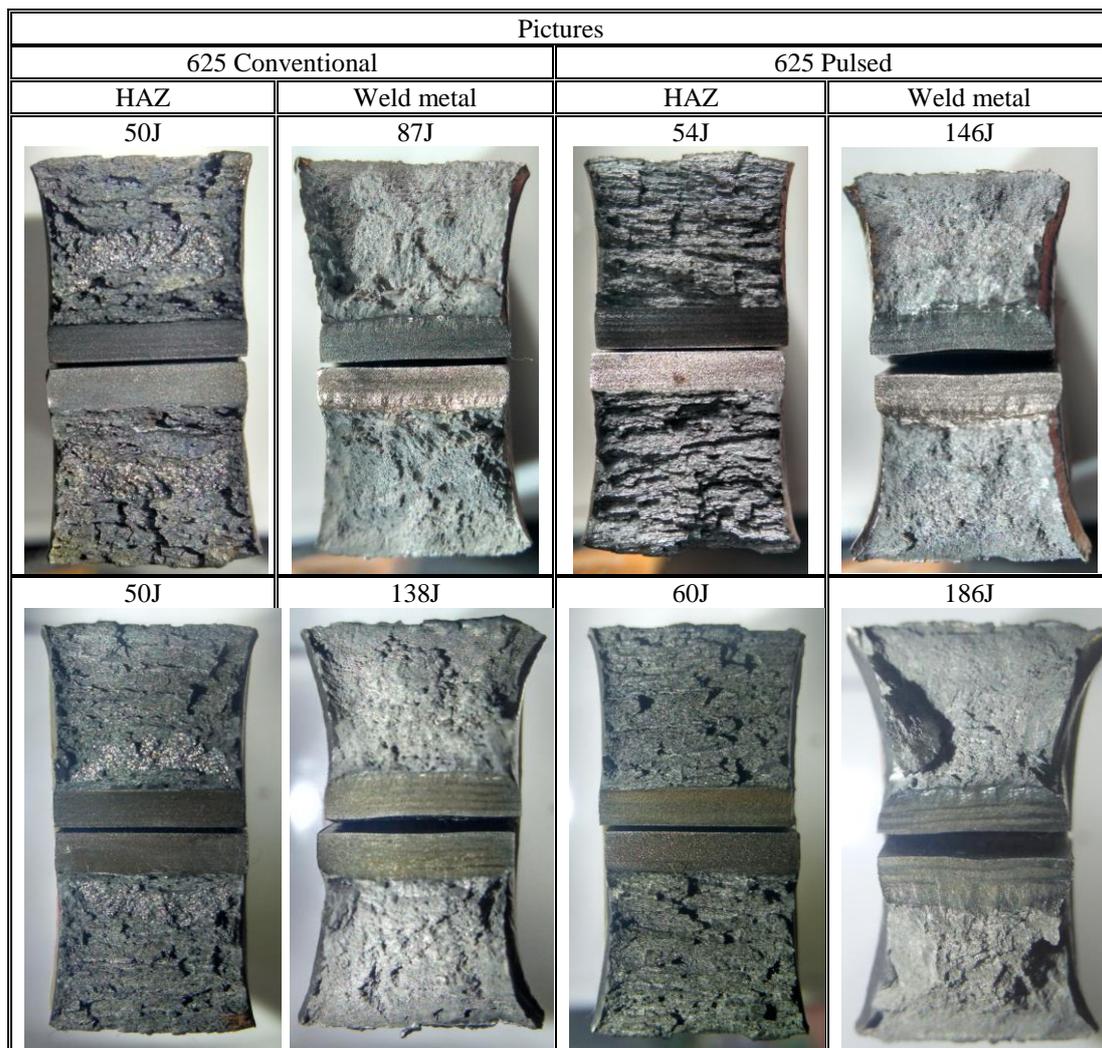


Figure 11. Appearance of the fracture after Charpy test of the samples.

The Figure 11 shows that the macroscopic aspects of fracture of the samples located in the HAZ, apparently presented very small lateral expansion with a weak ductile behavior, due to the fact that they presented a fracture mixed with bright regions, characterized by fragile behavior, and very low lateral expansion evidencing a behavior of ductile fracture, therefore characterizing the fragile ductile behavior. This behavior of the fracture can be justified by the fact that it is a heterogeneous region and with several phase transformations due to the cooling rates imposed by the welding process.

We can see in the region where the melt zone of the weld was fractured, the samples tested showed significant lateral expansion, which characterizes a ductile fracture, with considerable plastic deformation and section reduction, before the final rupture, as can be observed in the weld metal fracture of the conventional way where this behavior was more accentuated and due to greater absorption of its energy.

### 3.4. Hardness test

Table 7 presents the results of the hardness tests, the welded joint was evaluated according to NACE MR0175 standards, following the recommendations required for the evaluation of welded components.

Table 7. The average transversal hardness in the welded joint of the buttering 4130.

Condição	1ª Layer (HRB)	2ª Layer (HRB)	HAZ (HRC)	MB (HRB)
Current conventional	89.38	90.32	20.68	93.98
Current pulsed	89.64	87.82	20.00	97.48

The results shown in Table 7 for the HAZ are in HRC, which allows evaluating if the results are in agreement with the norm that recommends values of hardness not superior to 22 HRC. For the other evaluated areas, weld metal and base metal, the values presented are in the HRB scale, because during the tests it was not possible to determine the hardness in the HRC scale in these areas due to the values being below the scale range. As the proposed study is directed to the ZAC area, our evaluation will be directed to this area.

The values obtained in the HAZ were below that indicated by the standard that is 22HRC, which confirms that the hardness values obtained in the HAZ are approved following what is established by NACE MR0175, which characterizes the efficiency of the welding values used in the process and the heat stress relief treatment. This result corroborates with the studies of Fontes (2008), according to the author there are metallurgical effects imposed by post-welding heat treatments, which can affect the welded joint properties and that these effects depend on the welding values adopted (mainly heat input and preheating), the composition of the weld metal (type of consumable), among others.

## 4. CONCLUSION

The proposed objectives and the used methodology, together with the results analyzed and discussed, allow us to conclude that:

- For the tensile tests, the performance of the weld metal and the heat affected zone were superior to the base metal, proving the effectiveness of the welding parameters used.
- The pulsed current mode provided a more tenacious welded joint than the conventional current mode.
- The influence of the pulsed current mode was greater on the fracture toughness of the weld metal.
- The absorbed energies of all test samples met API 6A standards
- All hardness values obtained in HAZ are below 22HRC, meeting the standards of NACE MR0175.

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