

## Cold cracking, microstructure, notch toughness, transverse and longitudinal hardness to the weld joint of P460NL1 steel

### [Fisuración en frío, microestructura, tenacidad a la entalla, dureza transversal y longitudinal a la unión de soldadura del acero P460NL1]

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#### Resumen

Se evaluó el desarrollo microestructural, la dureza en HV10 longitudinal como transversal a la ZF y tenacidad a la entalla en pase de raíz y relleno a temperaturas de precalentamiento de 100 °C, 140 °C, 180 °C, 220 °C y 260 °C en la unión de soldadura del acero P460NL1, por FCAW en pase raíz y para relleno-acabado mediante el proceso SAW, el control de las temperaturas de precalentamiento de inicio y de interpase, se realizó por mantas térmicas y pirómetro digital. Los END de partículas magnéticas justificó la aceptación o rechazo de las probetas para el estudio. En puntos selectos de la unión de soldadura mostraron la dependencia de la dureza en función a la microestructura. A temperatura ambiente se observó fisuración en frío inmediata. En la ZAC, los microconstituyentes generaron zonas de alta dureza bajo el cordón y zonas de baja dureza debido a sobrevenidos, con presencia de ferrita Windmattatten, el aumento del precalentamiento determinó la disminución y algunas veces la no presencia de estructuras endurecidas. Los perfiles determinaron una disminución de la dureza a medida que se incrementó la temperatura de precalentamiento. En la ZF se observaron granos columnares con alta presencia de ferrita WF en sus diferentes morfologías y PF(G) y las zonas refinadas con microconstituyentes típicos. Se evidenció homogeneidad respecto de la tenacidad a la entalla a todas las temperaturas y el efecto de pasadas en la microestructura longitudinal lo cual evidencia lo beneficioso de la temperatura de precalentamiento al disminuir la dureza en zonas críticas y homogeneizar la unión soldada.

**Palabras clave:** Fisuración en frío; Dureza transversal-longitudinal, Microestructura, Acero P460NL1.

#### Abstract

Microstructural development, longitudinal HV10 hardness as transversal to the fusion zone and notch toughness in root and filling pass were evaluated at preheating temperatures of 100 °C, 140 °C, 180 °C, 220 °C and 260 °C in the weld joint of P460NL1 steel, by FCAW in root pass and for filling-finishing by means of the SAW process, the control of the start and interpass preheating temperatures was carried out by thermal blankets and digital pyrometer. The NDT of magnetic particles justify the acceptance or rejection of the specimens for the study. In selected points of the weld joint they showed the dependence of the hardness as a function of the microstructure. At room temperature, immediate cold cracking was observed. In the HAZ, the microconstituents generated areas of high hardness under the cord and areas of low hardness due to overturning, with the presence of Windmattatten ferrite, the increase in preheating determined the decrease and sometimes the absence of hardened structures. The profiles determined a decrease in hardness as the preheating temperature increased. Columnar grains with a high presence of WF ferrite in their different morphologies and FP (C) and refined areas with typical microconstituents were observed in the Fusion Zone.

Homogeneity was evidenced with respect to notch toughness at all temperatures and the effect of passes on the longitudinal microstructure, which shows the benefit of the preheating temperature by reducing the hardness in critical areas and homogenizing the welded joint.

**Keywords:** Cold cracking; Transverse-longitudinal hardness, Microstructure, Steel P460NL1.

## 1. Introduction

An important impulse in the evolution of high strength and low alloy steels (HSLA) has been determined by the need for: (i) high strength, (ii) improvement in toughness, ductility and formability, and (iii) weldability improved. In order to meet these somewhat conflicting requirements, the carbon content of the steel has been progressively reduced to below 0.10% C. The desired strength is largely achieved through a refinement of the grain size of the ferrite, produced by the additions of microalloying elements such as aluminum, vanadium, niobium, and titanium in combination with various forms of thermomechanical processing (Pickering, 1977). This refinement has made it possible to improve: the resistance of steels to hydrogen-assisted cold cracking (HCC), stress corrosion cracking (SCC), and brittle fracture initiation in the region of the heat affected zone of the weld joint (HAZ), without sacrificing base metal strength, ductility, or low ductile-brittle transition temperatures (Suzuki, 2009). Fine-grained steels for pressure vessels, pipes and boilers are thus named in accordance with the product designation and the manufacturing standard EN 10028-3, and the quality grades that designate these steels, and may be in delivery state, rolling mill, thermomechanical rolling or heat treatment in rolling ovens. The dimensions of the plates range from 12 mm to 200 mm in thickness and width from 1000 to 2700 mm and length from 200 to 14000 for widths from 1500 to 2000 mm; the maximum sheet weight is 15 tons.

The final microstructure of the weld metal (MS) will depend on the complex interactions between important variables such as: (1) The total alloy content, (2) the chemical composition, and the distribution of non-metallic inclusions, (3) The microstructure solidification, (4) The grain size of previous austenite, (5) The thermal cycle of welding. Although the microstructural changes in the cooling that takes place within the MS are through a critical range of transformation temperatures, in principle, they are the same as those that occur during the rolling and heat treatment of the steel, the existing conditions in the welding are significantly different from those used in steel production because of the strong non-isothermal behavior characteristic of the electric arc welding process. Oxygen is of particular interest in this regard, since a large number of oxide inclusions are known to strongly influence the transformation of austenite into ferrite, both by restricting the growth of austenite grains, as well as by providing sites favorable nucleation rates for various types of microstructural constituents (needle ferrite, ferrite side plates).

On the other hand, during the solidification of MS, alloying elements and impurities tend to segregate widely in the central parts of the interdendritic spaces under the quench conditions. The existence of extensive segregations also alters the kinetics of subsequent solid-state transformation reactions. Consequently, the transformation behavior of MS is observed to be quite different from that of MB, even when the nominal chemical composition has not been significantly changed by the welding process (Grong, 1986). Metallurgical studies have shown that the content of Nb or V carbides, by segregation, decrease toughness, others such as H and N, decrease them considerably. However, from the aforementioned, there is no doubt that the welding processes chosen will have a decisive influence, not only on the filler metal, but also on the HAZ, since they directly affect the thermal cycle that occurs in welding.

The impact properties and toughness of welded deposits are generally not high, this is mainly due to the inhomogeneity of the microstructure resulting from its relatively thick columnar solidification structure and high segregation and a large grain in general leads to a low toughness, and for this reason it is usual to find that microstructures containing a high percentage of acicular ferrite have good resistance to cleavage, while those containing regions of coarse-grained edge ferrite or ferrite with aligned second phases tend to have a low toughness (Muñoz, 2009) and embrittlement inside the HAZ in low-carbon steels occurs in the coarse-grained region adjacent to the melt line due to the formation of brittle microstructures such as plate ferrite

(Widmanstätten, upper bainite ) or grain edge ferrite, (Akelsen, 1987). Fragile failure predictive models consider that for a crack to propagate catastrophically, the concatenation of three events must occur at some point in the material (ZAC) subjected to stress (1) fracture of a carbide (induced by sliding). (2) the crack reaches the interface between the carbide and the matrix (bainitic package) (3) the interface between bainitic packages, (Moya, 2009).

Cold cracking is a mechanism that results from the action of hydrogen on a brittle microstructure under stress, (Banley, 1990) and the main cause is the high hardness and brittleness of steels as well as the harmful presence of hydrogen, according to ( Coloma, 2002) and (Granjon, 1989) hydrogen cracking appears after welding and at the end of the cooling cycle, due to the necessary time required for a sufficient amount of hydrogen to gather at a given point by diffusion from the humidity of the system and under the effect of the stresses inherent to the welding process. To avoid or reduce the risk of cracking of welded joints by hardening of the HAZ, the following measures should be taken into account: (1) Preheating to avoid the formation of martensite during cooling.

And (2) carry out a post-weld treatment, either a stress relief treatment or a tempering treatment to reduce the hardness of the HAZ. (3) Select a steel with a lower CE (CE <0.4%), which reduces the tendency to harden in the HAZ. The problem in the ZAC has alternative solutions such as preheating, adding microalloys and multipase welding and to what they refine the grain (Sindo, 2003), this allows to improve: the resistance of the steels to (HCC), corrosion under stress (SCC), and brittle fracture initiation in the HAZ region, without sacrificing base metal strength, ductility, or low ductile-brittle transition temperatures (Suzuki, 2009) and (4) Select a steel with lower% C (% C <0.2 ), which reduces the maximum hardness that can be achieved during cooling of a welded joint. For the notch toughness tests, a type V notch is generally used. A type U notch has been selected due to the greater experience of the authors in interpreting the results with this type of notch; In any case, there is a proportional relationship between the values obtained with both types of notch (Sreenivasan, Ray, Samuel and Manna, 1992). There is also a linear correlation between the values of Charpy notch toughness with V-notch, CV, and the values of opening against the crack, CTOD (Otarola et al. 2006) and, consequently, a correlation with the factor of Squared critical stress intensity, Kc2, of fracture toughness.

This allows us a comparative estimation of the fracture behavior for different welding conditions and for different notch positions with respect to the weld (Martinez 2011). The objective of the research is that the results serve to specify the WPS welding procedures on an industrial scale based on the preheating of the P460NL1 steel, the evaluation was in test tubes without preheating and preheating.

## 2. Materials and Methods

**2.1 Object of study:** It was the welded joint of P460 NL1 steel, marketed in the form of plates of 30 mm x 7000 mm x 4000 mm. Both longitudinal and transverse specimens were made for hardness and microstructure evaluations.

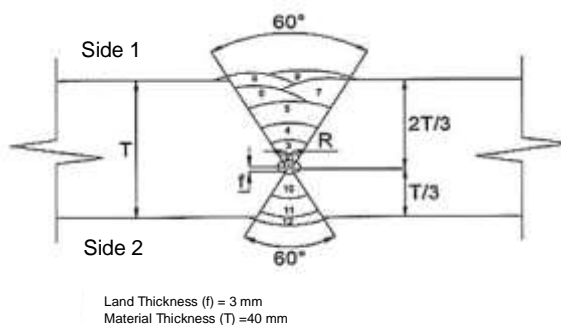


Figure 1. Multi-pass weld design of the welded joint and specimens selected for the study.

Table 1. Chemical composition of P460NL1 steel (% weight).

C	Si	Mn	P	S	Al	N	Cr	Cu	Mo	Nb	Ni	Ti	V
0.19	0.5	1.2	0.025	0.015	0.02	0.0025	0.3	0.6	0.12	0.07	0.8	0.02	0.2

Table 2. Chemical composition of the Dual Shield II K2 filler material wire, with carbon-manganese chemical composition and 1.2 mm diameter for the FCAW process

C	Mn	Si	P	S	Ni
0.19	0.5	1.2	0.025	0.015	0.02

Table 3. Chemical composition of Soldafill S2Mo filler material for the SAW process

C	Mo	Mn	Si	P	S	Cu
0.14	0.5	1.1	0.05	0.02	0.01	0.3

**2.2. Conditioning of specimens:** The assembly was prepared, cut, machined and made for cutting plates by oxyfuel and for beveling the P460NL1 steel plates at GCZ Fabricaciones, Lima. The plates to be welded will have dimensions of 6 "x 3"



Figure 2. P460NL1 steel plates, flame cutting and beveling machine for double V



Figure 3. P460NL1 steel plate shoring, double V joint, by FCAW



Figure 4. SAW filler welding process according to WPS

The welding process was carried out following a WPS established according to the ASME IX standard, after characterizing the sample under study. The weldability of P460NL1 steel was determined, prior to welding. After cleaning the plates, they were arranged according to the order of the sequence of randomized tests, according to a previous design to test the hypothesis. 02 weld beads were deposited, in multipage, for FCAW and 05 multipass SAW beads for each particular specimen.



Figure 5. Control of preheating and interpass temperature



Figure 6. Specimens sectioned and prepared longitudinally and transversely for hardness measurements.

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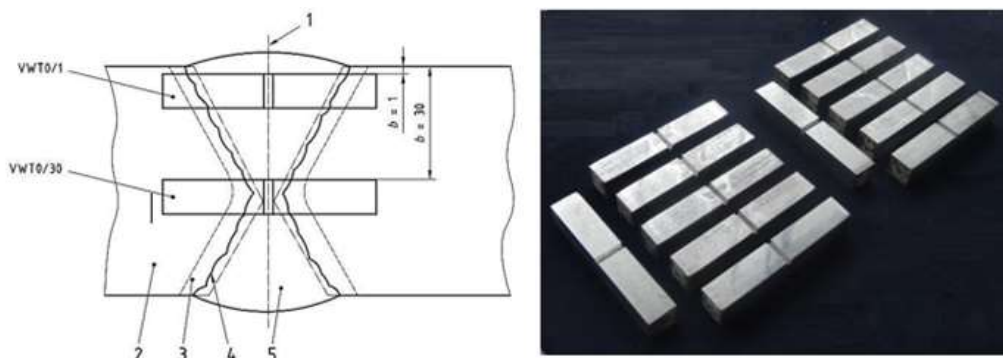
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Figure 7. Cross section for obtaining specimens to evaluate notch toughness

The specimens that were prepared according to position VWT0 / 30 corresponding to the fusion zone and as shown in Figure 7. and according to the European standard "Destructive tests on welds in metallic materials-Impact tests: 2011: 5). Specimen for locating the notch according to ISO 9016: 2001, with dimensions (10x10x55mm).



Figure 8. Specimens with hardness measurements, at the top and bottom, the durometer and the Leica DM600M microscope, used in the investigation.

The surface was prepared by roughing from 220-2000 sandpaper and polishing was carried out up to grain size 1, 0.3 and 0.05  $\mu\text{m}$  of granulometry of the alumina powder in suspension. After polishing, it was chemically etched with 2% Nital and Vilella reagent. Observations will be made by metallographic microscope, Figure 8. An average of 21 HV10 hardness measurements were made along each sectioned specimen, covering MB, ZAC and ZF. The width of the ZAC was measured at both ends of the bead.

The specimens were tested to obtain the notch toughness of the welded joint at the Sider Perú SA Company, Chimbote - Ancash in the Physical Testing and Quality Control laboratory at room temperature of the different preheating levels corresponding to each specimen.

### 3. Results

3.1. From the hardness of the welded joint of P460NL1 steel in double V, transversal.

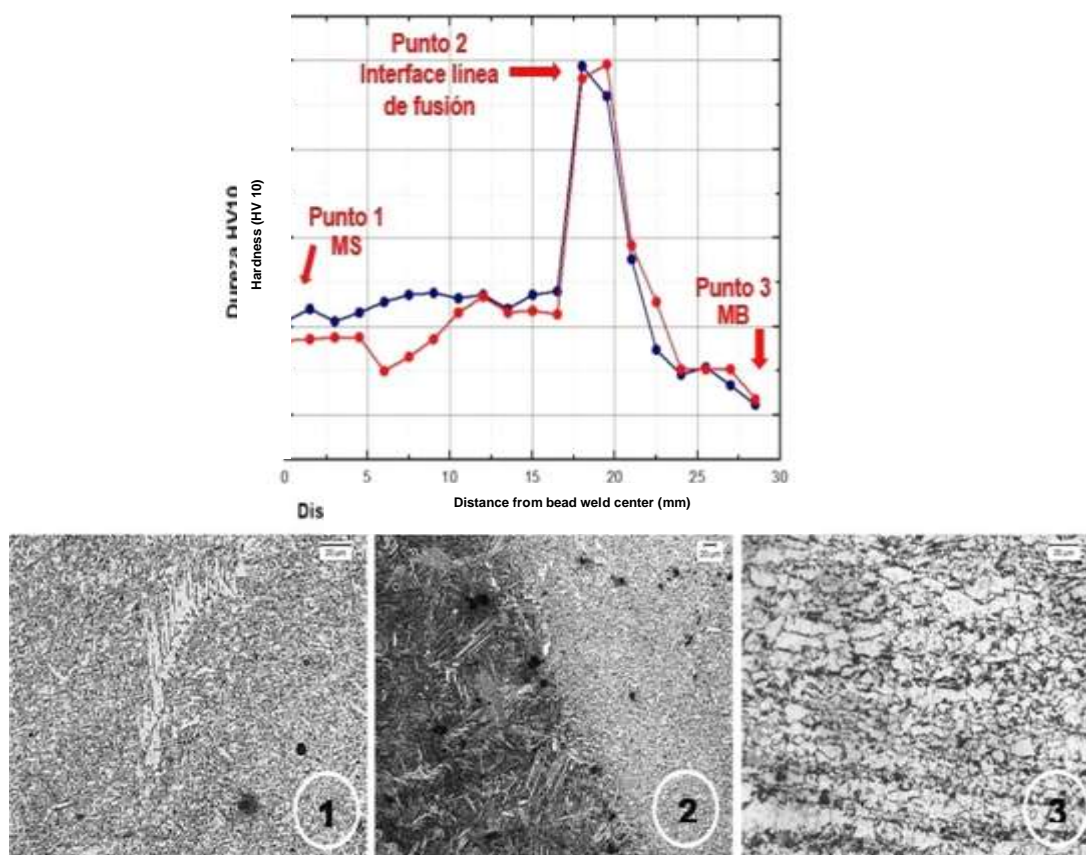


Figure 9. Hardness profiles of the welded joint of P460NL 1 steel, by FCAW process, in root pass and SAW filling, specimen without preheating

The hardnesses were done on the HV10 scale and were 2 mm from the surface from the center of the fusion zone towards the base metal. For specimens without preheating, Figure 9. It was observed that the weld metal (MS) is microstructurally characterized by columnar-type morphology due to the effect of solidification, with the presence of ferrite in lateral plates, with average hardnesses of 198 HV10 (point 1). At the interface or fusion line (point 2) the hardnesses corresponding to the HAZ reached an average of 339 HV10 and the microstructure corresponded to hardened structures that would allow susceptibility to cold cracking to an unlikely degree, the structures showed bainites, ferrites widmanstatten, those that provide fissure nucleation sites, as proposed by Sindo, 2003, The base metal (MB) is of the ferritic type, point 3, with an average hardness of 172 HV10.

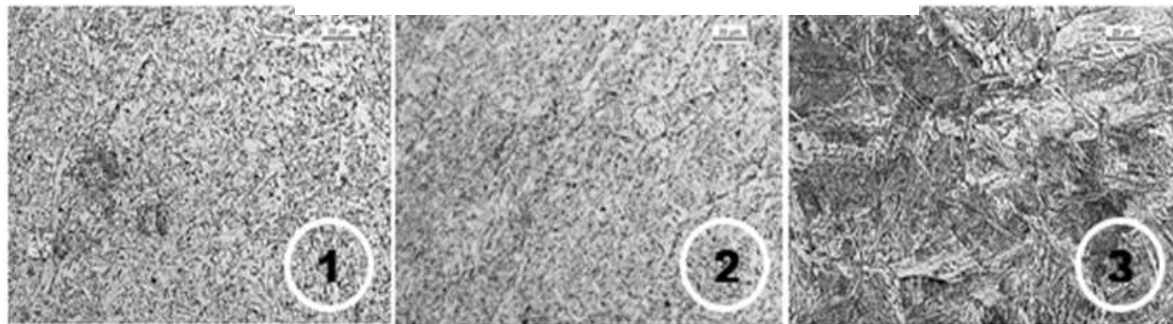
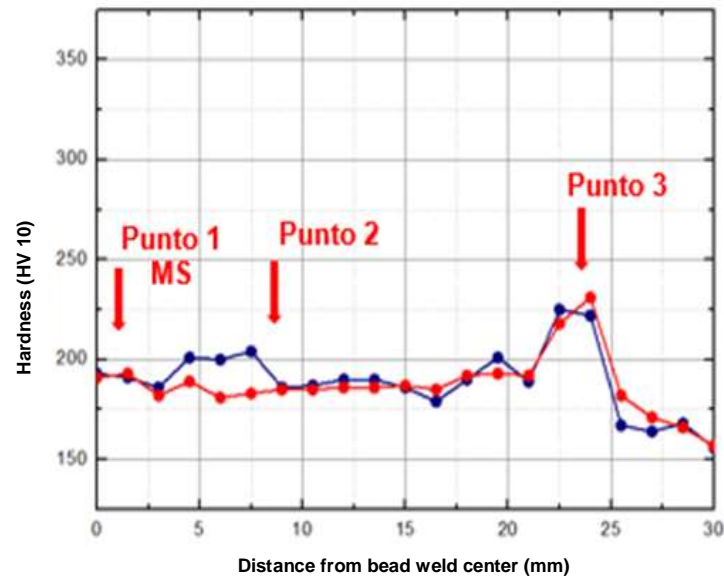


Figure 10. Hardness profiles of the welded joint of P460NL1 steel, by means of FCAW process, in root pass and SAW filling, preheating 220 ° C. Points 1,2 and 3 represent distance shots from the center of the weld bead.

Figure 10, corresponding to a preheating temperature of 220 °C, it was observed that MS is characterized by acicular ferrite, limiting the presence of ferrite in plates, this is due to the decrease in the cooling speed produced by the preheating temperature elevated (Grong, 1986). At point 1 we have hardnesses of 192 HV10 which preserves a characteristic hardness in comparison with the previous temperatures, taking into account only the microstructural change of the ferrite; in point 2 corresponding to ZAC we have the decrease in hardness to 227 HV10, without any risk of cold cracking according to (Fosca, 2003) it was also observed the presence of structures, acicular ferrite and ferrite in the grain limit which are structures more ductile favorable to welded joints of this type. At point 3, we obtain hardnesses of 168 HV10, corresponding to acicular ferrite.



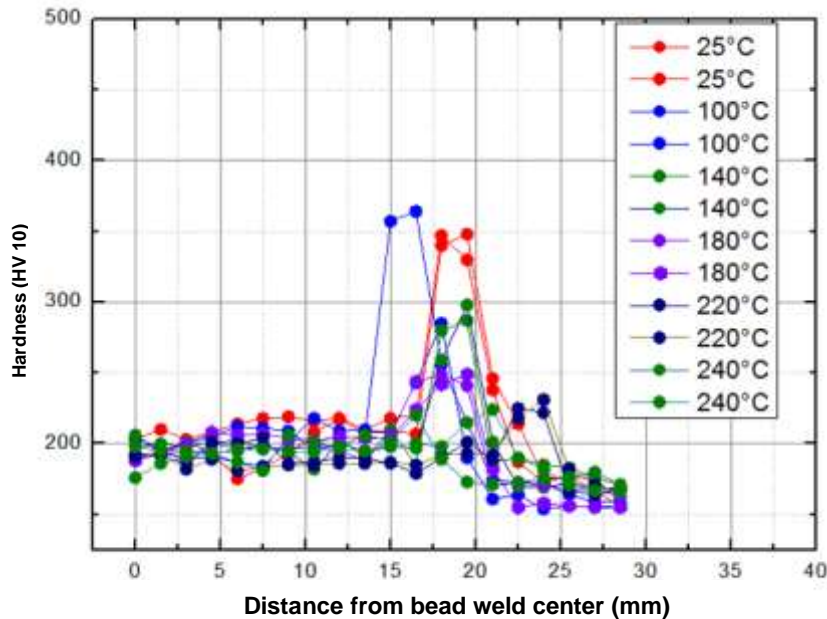


Figure 11. Consolidated hardness profiles of the welded joint of P460NL1 steel, using the FCAW process, in root pass and SAW filling.

In Figure 11. we have the consolidation of hardness profiles which allows us to observe the effect of the preheating temperature corresponding to each assigned temperature, it is determined that from the temperature of 140 °C onwards the risk of cold cracking is zero of According to (Fosca, 2003) at this temperature, hardnesses were approximated to 260 HV10. An increase in the preheating temperature from 100 °C to 260 °C produces a marked microstructural change of MS and ZAC, which is explained in the continuous cooling transformation diagram (CCT) for this steel, which shows that when increasing the preheating temperature decreases the microphases inside the austenite grains can change from FP (I) and PF (G); This is in accordance with what is proposed by (Olson, 1996).

**3.2. From the hardness of the welded joint of P460NL1 steel in double V, Longitudinal.**

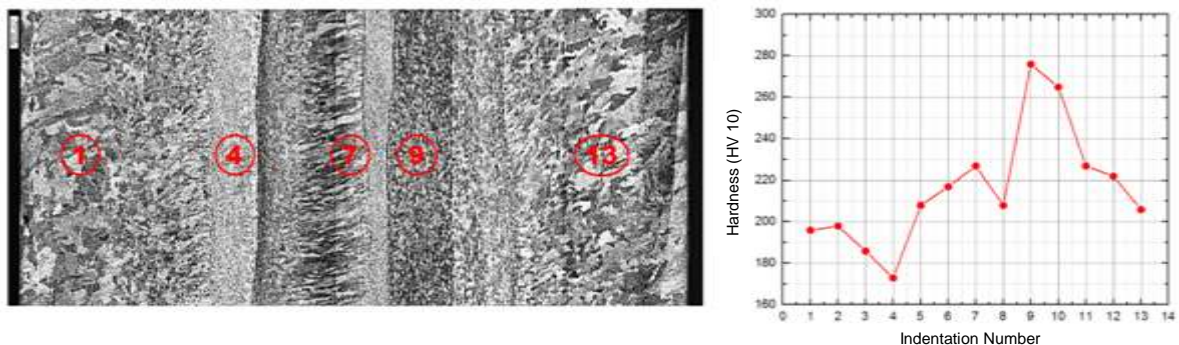


Figure 12. Longitudinal hardnesses of the welded joint without preheating covering FCAW and SAW processes. 1,4,7,9 and 13 represent the number of indentations performed

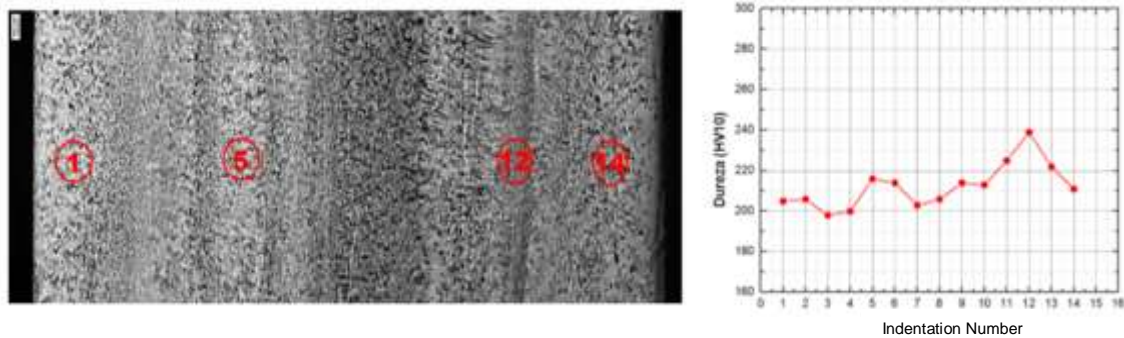


Figure 13. Longitudinal hardnesses of the welded joint at preheat temperature 220 °C covering FCAW and SAW processes. Points 1,5,12 and 14 correspond to the number of indentations made.

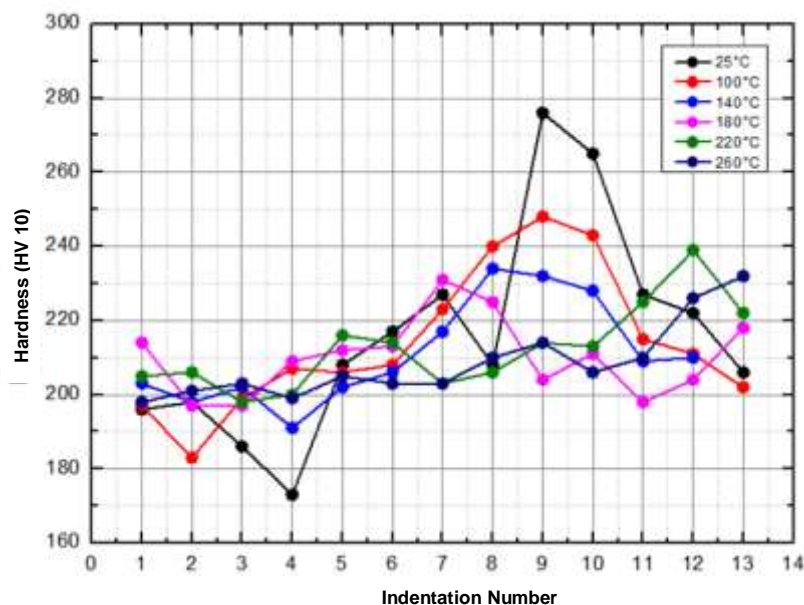


Figure 14. Consolidated root pass hardness profiles, longitudinal FCAW process.

The longitudinal hardness sweep of 1mm distance between indentations was carried out, which were located in central areas (FCAW) and hardnesses were taken at the points corresponding to the established distances, it was determined that by increasing the preheating temperature the hardness was decreased As can be seen in Figure 13 with respect to Figure 12. Strata corresponding to the deposits overcooked by multipases were observed, showing the SAW process with coarse-grained columnar grains and in internal areas with fine columnar grains. In Figure 14. Consolidated longitudinal hardness profiles for all preheating temperatures where from a temperature of 180 °C we have a much more homogeneous behavior in the distribution of hardness, satisfactorily executing the preheating temperature in the decrease of the cooling speed obtaining less brittle and more ductile microstructures beneficial to avoid cold cracking and propagation of cracks in welded joints subjected to external loads.

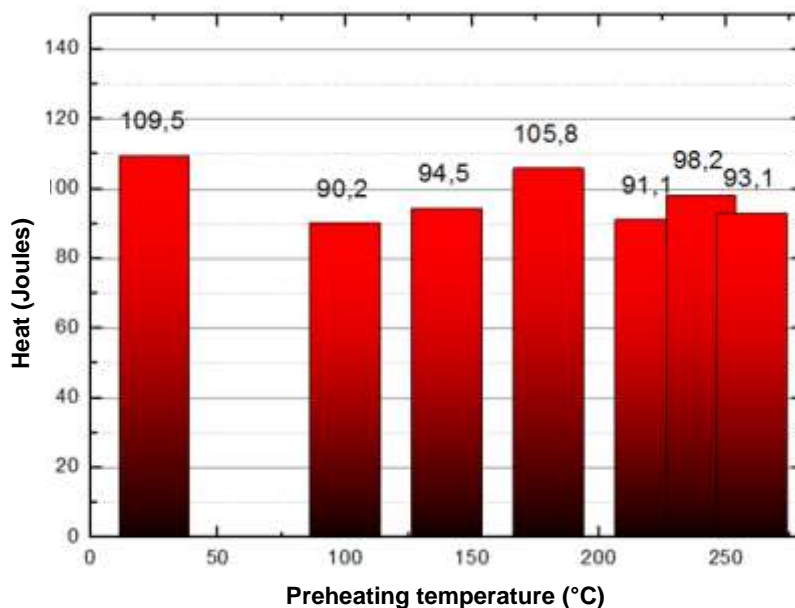


Figure 15. Results of notch toughness with Charpy type V notch of specimens in the MS zone for the root pass, FCAW process.

### 3.2.2. From the fill-finish zone, SAW process

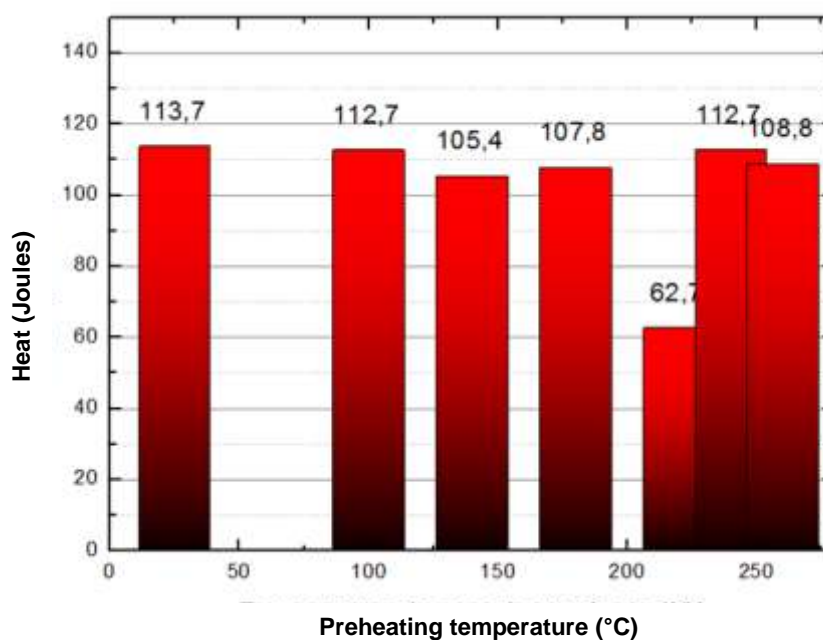


Figure 16. Results of notch toughness with Charpy type V notch of specimens in the MS zone for the root pass, SAW process.

The Charpy type test tests with V-notch of the welded joints were carried out in two different zones which are the FCAW root pass and the SAW fill pass as shown in Figure 15, where the dimensions of the specimens are specified. according to the European standard SS-EN ISO 9016: 2011 (Figure 7.) The specimens corresponding to the FCAW zone show lower values of toughness (98 J, on average) compared to the SAW zone (105 J, on average) where we can say that the last fill pass considerably affects the welded joint depending a large part of its efficiency on it. In the test piece corresponding to the preheating temperature 220 °C shows a considerable decrease in toughness 63 J it is presumed that what could determine these values are the welding defects (porosities, lack of fusion, etc.), defects that had repercussions markedly at the time of impact testing, since the fracture in these specimens exactly started and propagated in the fusion line, specimens welded without preheating cannot be free from the possibility of cracking, and preheated specimens can also suffer from it, It should be noted that this possibly not only involves the welding procedure (if it had unwanted inconveniences or the performance of it did not have the necessary quality control) but it may also have occurred due to different factors. On the other hand, it could be seen that the bending angle of the different tested specimens is the same for all experiments. The appearance of breakage, of a grayish and fibrous character in the welded specimens, is confirmed as indicated above in comparison with the base metal, whose fracture is of a more fragile nature (Martinez, 2011).

#### 4. Conclusions

The microstructural analysis of the weld bead both in the FCAW root pass and SAW fill pass showed the following behavior:

- a) A small extension of the HAZ, compared to structural steels.
- b) The coarse-grained HAZ was small, the previous austenite grain size large, and the fine-grained HAZ was larger, in the first one, hardened structures were found in specimens without preheating.
- c) The intercritical affected zone is small compared to the fine-grained HAZ zone.
- d) An increase in the preheating temperature from 100 °C to 260 °C produces a marked microstructural change in MS, which is manifested with an increase in ferrite at the edge of grain PF (G), an increase in ferrite was also observed recrystallized and a decrease in acicular ferrite FP (I). The range of preheating temperatures from 100 °C to 260 °C, produces a decrease in hardness which is beneficial in reducing the possibility of cold cracking, likewise it was observed in the zone affected by heat there are non-hardened structures evidenced due to the presence of ferrite in greater quantity, behavior observed both transverse and longitudinal.

The hardness profiles determined that increasing the preheating temperature decreases the transverse and longitudinal hardness and the width of the HAZ.

The Charpy test with type V notch showed that the SAW fill pass has higher tenacity than the FCAW root pass because the latter bead is decisive within the welded joint, showing an acceptable behavior of the welded joint due to the homogeneity of the toughness in welded joints.

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