Effect of Welding Parameters on the Partially Diluted Zones Formation at Dissimilar Metal Welds

Norton Zanette Kejelin
Labsolda/EMC/UFSC
88040-900 Florianópolis - SC
norton@labsolda.ufsc.br

Augusto José de Almeida Buschinelli
Labsolda/EMC/UFSC
88040-900 Florianópolis - SC
buschi@emc.ufsc.br

Alexandre Meireles Pope
PETROBRAS
apope@petrobras.com.br

Abstract. *An experimental study was conduced in order to evaluate the weldability of API X-60 micro-alloyed steel pipes with E NiCrMo-3 (Inconel 625®) filler metal. These dissimilar joints exhibit usually small localized hard zones along the fusion boundary, which can show hardness exceeding VHN 400, referred here as Partially Diluted Zones. The objective of the work was to determine and mainly to optimize the welding parameters that have most influence on the extent of the partially diluted zones formation. The selected base and filler materials were those commonly used by Petrobras™ for dissimilar metals welding: type E-9018 D1 electrodes with 2,5 mm diameter for buttering passes and E-NiCrMo-3 with 3,25 mm diameter for weld depositions; API 5L X-60 steel pipes with 20 mm thickness and 254 mm diameter as the base metal. Metallurgical investigations were done with optical and scanning electronic microscope associated with Vickers microhardness tests to characterize the dissimilar hard zones structures. Thermal cycles were estimated by a thermal software simulator. The results can be used for the dissimilar metal welding parameters recommendations. Maintaining an optimum cooling rate and interpass temperature for a given base metal thickness, and controlling the carbon dilution of the base metal throughout welding resulted in drastic reduction of partially diluted zones formation. Another guideline adopted in this study was to accomplish buttering passes with similar E 9018 G (0,05% C) filler metal, promoting in this way, less carbon dilution at the subsequent Inconel 625® deposition. Post welding heat treatment were also evaluated in samples that contained PDZ's and a detrimental effect on the weld properties was observed above 540 ºC.*

Keywords*:* dissimilar metal welds, nickel based filler, partially diluted zones, fusion boundary and thermal cycle.

1. Introduction

Due to corrosive characteristics of Campos's Basin oils, the use of high strength low alloy steel (API X – 60) for rigid production risers is being evaluated, which have an internal coating with a nickel based alloy in the more susceptible parts to the fatigue-corrosion damage, typical of the aggressive environment in the petroleum off-shore extraction. The presence of the internal coating demands that the circumferential weld be performed with similar filler metal (in this case AWS E NiCrMo-3 commercially known as Inconel 625), selected to preserve the anti-corrosive characteristics and to give a weld metal deposit that can accommodate dilution from the base metal without result in a crack sensitive microstructure.

This subject was presented recently in a technical work in the I ENSOLD (Pope et al, *2004*), that contributed with positive data about the fracture toughness of that dissimilar joints types, rarely found in the literature. However based on their own observations and some other works, a troublesome factor was pointed by the authors: the formation of the discontinuous, hard (in the range of 300 – 450 HV) and brittle zones, or simply "Partially Diluted Zones" (PDZ) along the fusion boundary, on the transition interface between the ferritic base metal and the austenitic weld metal.

A great number of authors, Doody (1992), Kou (2003), Kvaale (2003), Omar (1998), Pope (2004), Rowe (1999),Wang (1993) and Welding Handbook (1998), mentioned PDZs as "Intermediate Diluted Zones", "transition zones", "unmixed zones", "filler-metal-depleted area" and even "hard zones", that can develop in the weld metal or heat affected zones (HAZ) during solidification of dissimilar welds. These hard regions have preferentially martensitic structure, but intermetallic constituents as sigma or chi phases are also reported to be present, although these are products of solid state transformation (usually after exposure to temperatures between 425 and 900ºC).

This paper reports some preliminary results of an investigation on the factors that affect the PDZs formation in an effort to develop practical procedures to reduce or avoid their presence in dissimilar metals welds.

2. Background

Since 1940 Cr-Mo heat resistant steels and austenitic stainless steels have been widely used in power plant construction and chemical industry. Simultaneously a great number of austenitic electrodes were developed, and has been used in the welding of dissimilar austenitic/ferritic joints, that became more popular and important, mainly for economical reasons, once they allow that just the more noble member of the joint be specified where larger heat and/or corrosion resistance be requested.

High strength low alloy steels can be easily welded, by different fusion welding processes, with nickel base filler metals. The composition and microstructure of the bulk fusion zone in dissimilar metal joints can be easily and reasonably estimated by simple dilution calculations and the Schaeffler diagram. The welding filler metal must be selected among the several commercial available consumables to produce a fusion zone with a microstructure of austenite or austenite plus ferrite even after dilution of the base metal, without resulting in a crack sensitive microstructure.

Although arc welding involves rapid and non equilibrium transformation conditions, it is assumed that the weld metal deposited by each pass possesses homogeneous composition, due to occurrence of strong hydrodynamic mixing forces in the molten pool. Nevertheless an additional problem found in dissimilar welds, where the chemical composition of the filler metal is very different from that of the base metal, is the inherent formation of very small, brittle and hard zones along the fusion line, which possesses intermediate composition between the base metal and the bulk weld metal. Its chemical composition is only measurable by chemical microanalysis. These regions, not estimated by the use of dilutions calculations, are here referred to as PDZs.

Doody (1992) reported about the deleterious influence of intermediate diluted zones on the stress corrosion resistance of dissimilar metal welds for sour service; he classified the morphology of these hard zones as "bays", "islands" and beachs".

Ornath *et al.* (1991 apud Kou 2003) determined the composition profiles across the fusion boundary of low alloy steel welded with a stainless steel filler metal of Fe-18Cr-8Ni-7Mn. They find a decrease in the alloy elements from the weld metal to fusion line, and proposed that segregation (rejection of Cr, Mn and Ni) rather than diffusion in the transient initial of solidification is responsible for the observed composition profiles.

Baeslack and Savage (apud Welding Handbook 2000) proposed that the convective movements in the molten pool (originated from the electric arc) is not strong enough for thorough mixing of the diluted base metal, however, intense enough to enrich this narrow not mixed nor diluted parts in alloy elements (Cr, Ni, Mo, Mn), increasing the local hardenability which associated with cooling rate form the PDZs.

Independent of above mentioned theories, the fact is that the partially diluted zones formation will depend basically on the following factors: chemical composition of both base and filler metals, welding energy and base metal thickness, or in other words: weld's chemical composition, dilution of the base metal and cooling rates.

3. Materials and Experimental Procedure

The base and filler materials selected for this study are commonly used in the Petrobras™ for dissimilar metals welding: Type E-9018 D1 with 2,5 mm diameter for buttering passes and E-NiCrMo-3 with 3,25 mm diameter for weld depositions. API 5L X-60 steel pipes with 20 mm thickness and 254 mm diameter were selected as the base metal. The chemical compositions of these materials are listed in table 1:

Table 1: Chemical compositions of Base and filler metals (wt %).

	C	Si	Mn	P	Cr	Mo	Ni	Al	Co	Cu	Nb	V	Fe
API X-60(1)	0.122	0.28	1.15	0.012	0.036	0.042	0.021	0.03	0.04	0.015	0.043	0.044	98.0
E NiCrMo-3(2)	0.04	0.50	0.60	-	22.0	9.0	61.6	-	-	-	3.30	-	3.0
E 9018 D1(2)	0.06	0.30	1.20	-	-	0.35	0.80	-	-	-	-	-	96.7

(1) Verified by chemical analysis.
(2) Manufacturing companies data.

Shielded Metal Arc Welding (SMAW) process was selected due to low costs and inherent facilities but the mainly factor is the environmental conditions in offshore welding operations. For this investigation all welds were fabricated by semi-automatic process by the "bead on plate" single and multi-pass welding techniques. Dissimilar metal welds (E NiCrMo-3 depositions) with 910 J/mm were done in three pass welding and PDZs formation was evaluated for three different conditions: welds without pre-heat, without pre-heat but submitted to "post welding heat treatments" (PWHT) for three hours at 420 ºC, 540 ºC and 660 ºC and welds with preheat temperatures of 100–130ºC and 200–230ºC.

Also base metal buttering in double layer technique with E 9018-D1 (850 J/mm of welding energy) was applied at 25ºC and 200–250ºC preheat temperatures, with the purpose to offer a substratum with less carbon content for the posterior Inconel® deposition, as a procedure to reduce the PDZ formation. Initially single-pass bead on plate welds with E 9018-D1 in three welding energy conditions (570 J/mm, 710 J/mm and 850 J/mm) were conduced and the joint characteristics evaluated.

Cooling times for the temperature range from 800ºC to 500ºC for different welding conditions were estimated by the methodology proposed by IRSID *(1977),* which is based on experimental welding procedures for carbon and HSLA steels and correlates welding energy with joint geometry and process efficiency, supplying the real energy transferred to workpiece. The real welding energy (heat input) associated with preheat temperature determine the cooling time for a temperature range from 800ºC to 500ºC.

Multiple transverse metallographic cross sections of all welds conditions were prepared for microstructural characterization using optical metallography and Vickers microhardness tests with 100 and 200 g. Scanning electron microscopy with energy dispersive X-ray spectroscopy (EDS) was applied for chemical analysis of weld. As carbon has a low atomic mass and it's not measurable by the common EDS microanalysis the carbon content for multipasses welding was estimated as a function from dilution, using equation 1. For the PDZ, the dilution can only be indirect known through the X-ray spectrum of others elements as Ni, Cr and Fe and knowing the chemical compositions of both base and filler metal.

$$\%X_{WM} = X_{BM} D + X_{FM}(1 - D) \tag{1}$$

Where: "X" is the element, "D" is the Dilution, "WM" weld metal, "BM" base metal and "FM" the filler metal.

4. Results and Discussion

4.1 Preferential Localization of PDZs

When welding the low alloy steel API-X60 with a high nickel consumable (compositions in Table 1), in agreement with the Schaeffler diagram (figure 1), the bulk weld metal will be fully austenitic, even for an unusually high dilution in the order of 70%. Nevertheless the microanalysis results presented in Table 2 (for the deposition with 1.100 J/mm) indicate for the PDZ an intermediate composition between that from base metal and filler alloy, so that depending on the cooling cycle a martensitic microstructure can be expected. Figure 1 illustrates a typical martensitic microstructure band along the fusion line. Further, as shown in figure 2, it was observed that hard zones form in a preferential region (bottom of the bead), so that a PDZ may be present under an individual weld bead, while the major portion of the interface between weld and base metal should not exhibit any heterogeneity.

Table 2: Composition of fusion zone (bulk weld metal and PDZ) as determined by microanalysis

	Fe	Ni	Cr	Mo	Mn	Si	Nb	C(1)	Dilution%	Cr_{eq}(2)	Ni_{eq}(2)
Weld Metal	28.7	45.0	16.1	6.6	0.75	0.44	2.41	0,06	27	24.6	47.2
PDZ	85.2	8.34	3	1.25	1,08	0,31	0.48	0,11	86.5	5.0	12.2

(1) Dilution calculations estimative.
(2) Schaeffler equivalents.

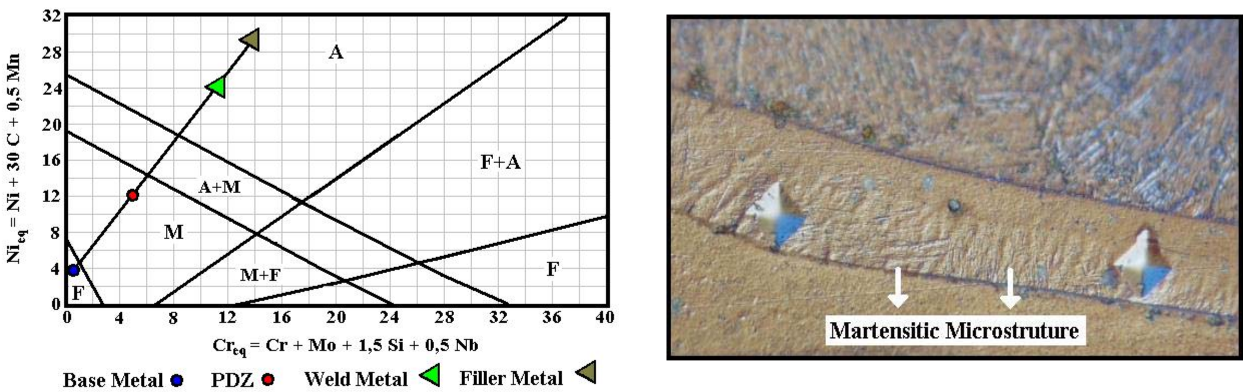

Fig. 1: Schaeffler diagram. Right: Martensitic PDZ along the fusion line. (500x).

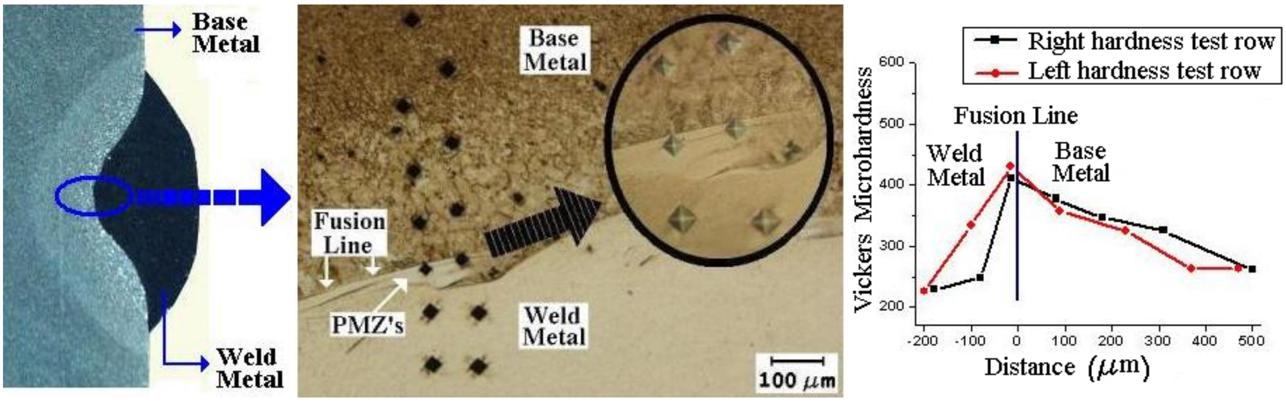

Fig.2: Dissimilar metal weld cross-section indicating PDZ. Right: Microhardness profile showing peak hardness above 400 HV at the fusion line.

4.2 Effect of Welding Energy and Preheat Temperature

Bead on plates with a similar filler metal (E 9018 D1), represented in fig. 3 (cases A, B and C), reveal that for welding energy equal or below 710 J/mm high hardness (above 350 HV) is observed in the grain coarsened HAZ of the API-X60 base metal. These hardness levels are characteristic of a martensitic microstructure and should be avoided by more strict specifications: use of welding energy equal to or above 850 J/mm for 20 mm wall-thickness or adequate preheating requirement.

On the other side, dissimilar metal bead on plates even when deposited with a higher welding energy (910 J/mm in figure 3D) showed high CG-HAZ hardness, above 400 HV. These at first view unexpected results could only be explained by a lower thermal efficiency and therefore a lower heat input when welding with ENiCrMo3. Table 3 correlates the welding energy for E9018D1 and ENiCrMo3 electrodes with the HAZ and weld metal characteristics and with the respective cooling time form 800ºC to 500ºC. It should be observed from table 3 that the minimum $\Delta t_{(8-5)}$ necessary to avoid martensitic structures formation in the CGHAZ is above of 3s.

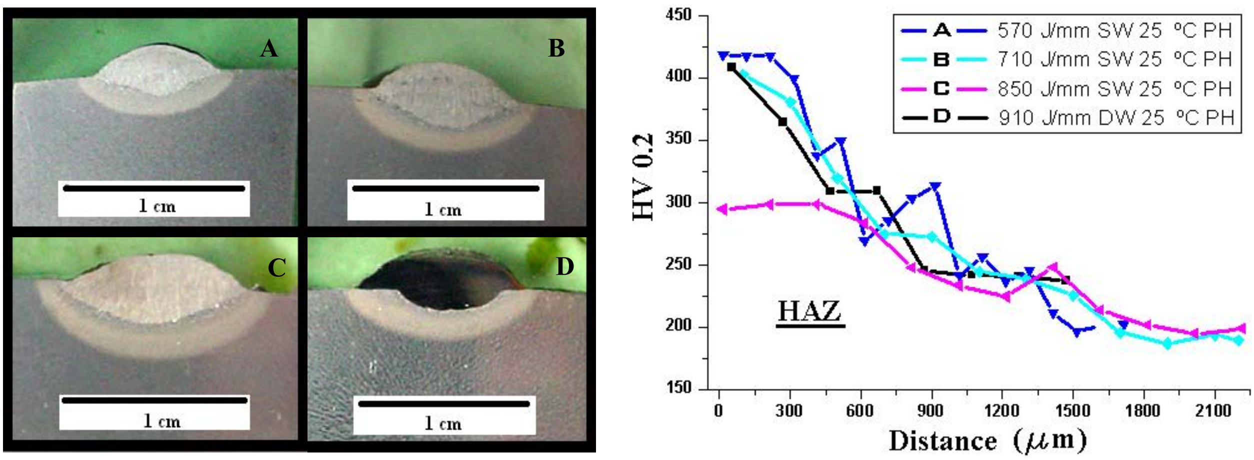

Figure 3: transversal section of Bead on plate depositions. Right: Respective microhardness.
SW: similar welding. DW: dissimilar welding.

Table 3: Characteristics of bead on plate welds.

Weld	Filler Alloy	Welding Energy (J/mm)	Width of HAZ (mm)	Penetration of HAZ (mm)	Width of Weld Metal (mm)	HAZ $HV_{(0.2)}$	Heat Efficiency [1]	Δt 8-5 (s) [2]
A	E 9018 D1	570	8.8	0.23	7.0	420	0.8	2.2
B	E 9018 D1	710	9.8	0.31	7.9	406	0.8	2.8
C	E 9018 D1	850	12.7	0.39	10.2	299	0.8	3.3
D	ENiCrMo3	910	11.7	0.30	10.0	413	0.67	3.0

(1) Heat efficiency estimation according to Santos (2001).
(2) Cooling rates estimation according to IRSID (1977).

Partially diluted zones were observed even under preheating, but in these cases, their extension, hardness and quantity was reduced. Photomicrographs in figure 4 show the weld interface for preheat temperatures of 100–130ºC and 200–230ºC. Hardness measurements (right side) indicate the influence of the preheat temperature on the weld metal and heat affected zones: as larger the preheat temperature, the smaller is the hardness at those regions. It could also be noted in the fig. 4c that by preheating at 200–230ºC an discrete formation of PDZ is observed in just specifics regions along the bottom of the first bead, while the major part of fusion line extension (fig. 4d) is kept free from partially diluted zones. Table 4 shows the effects of different preheat temperatures on maximum PDZ and HAZ hardness for dissimilar metal welds fabricated with 910 J/mm of welding energy and 0.67 of thermal efficiency.

Table 4: Characteristics of dissimilar multipass welding

Preheat $_{(ºC)}$	$HV_{(0.2)}$ PDZ	$HV_{(0.2)}$HAZ	Δt 8-5 $_{(s)}$ [1]
25	475	413	3.0
100-130	423	286	3.86
200-230	412	241	5.7

[1] Cooling rates estimation, according to IRSID (1977).

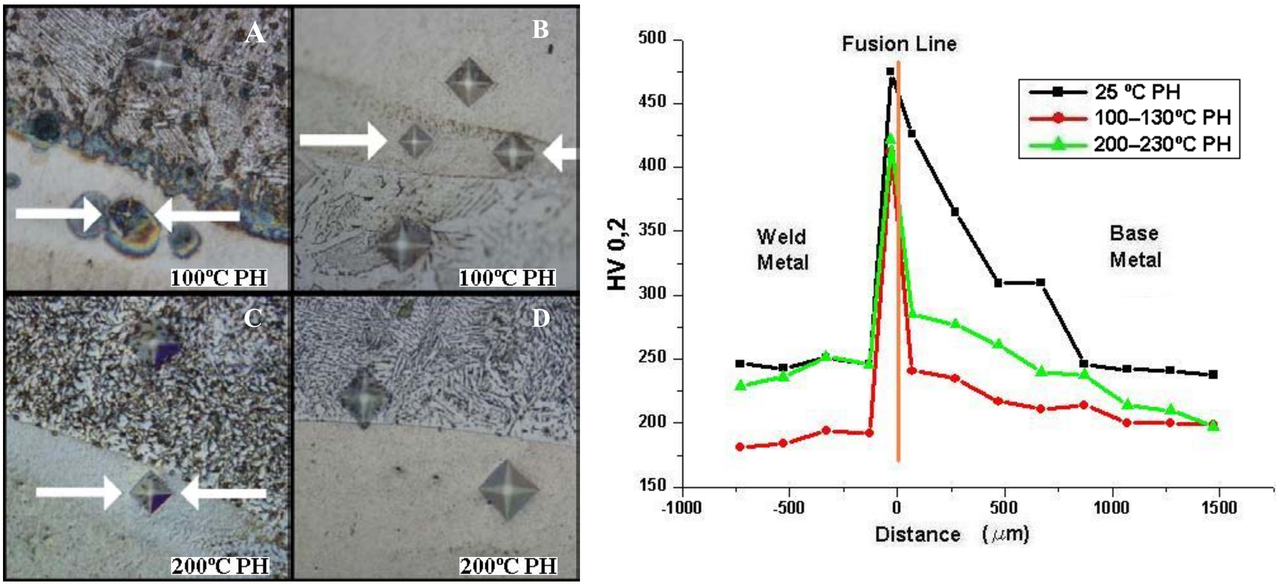

Figure 4: Weld interface showing the effects of the different preheat temperatures (100ºC and 200 ºC), 500x. Right: Respective (HV 0,2 kgf) microhardness indentations.

4.3 Evaluation of the Buttering Parameters with E 9018-D1 Electrodes

Positive effects of buttering are clearly visible on the hardness profiles in figure 6: for room temperature, a softening of the PMZ (represented by the peak hardness values) and respective HAZ was observed when compared to dissimilar welds without buttering and preheat. This is a positive consequence of the carbon reduction at the substratum fabricated.

Buttering with E 9018-D1 electrodes, using 850 J/mm as welding energy, corresponds to 60% of base metal dilution. This way the carbon content in the first buttering layer, estimated by the dilution calculations, is approximately 0,09 %, while in the second pass of double layer buttering, this value is around 0,08%.

The combined effects of buttering and preheat/interpass temperature in range of 200-230ºC for every (buttering/deposition) passes, resulted in a drastic reduction of the partially mixed zones formation. The respective $\Delta t_{8\text{-}5}$ for these dissimilar welds was approximately 6,3 s. However evidences of PDZ formation with high hardness of 395 HV were founded in one of three samples examined.

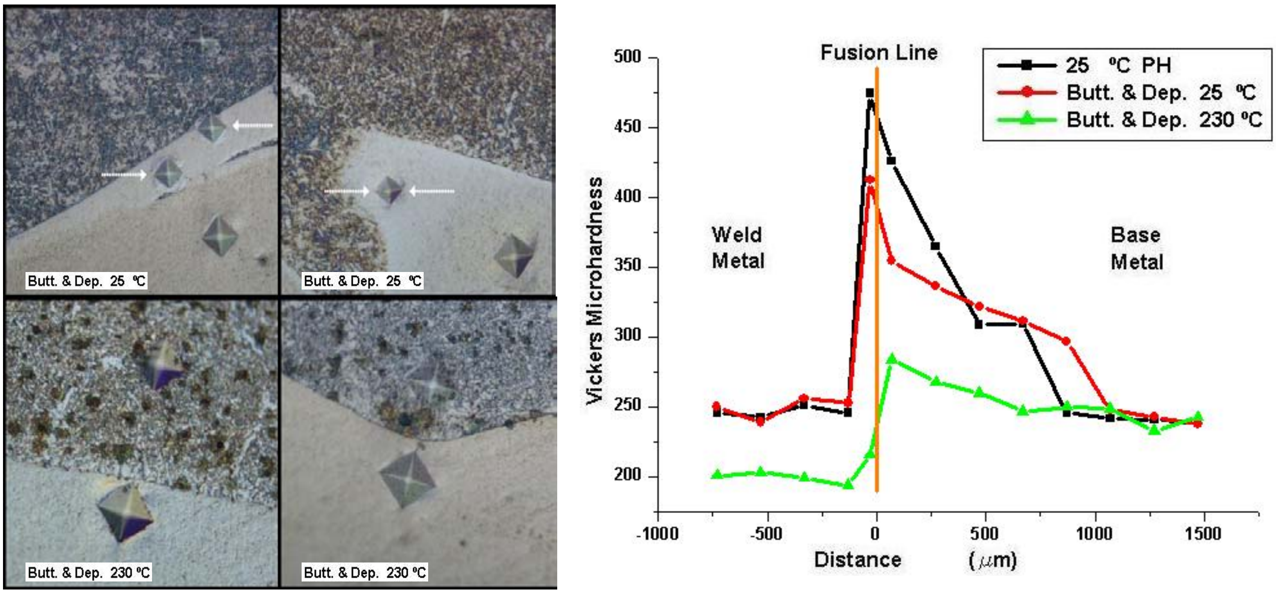

Figure 6: Dissimilar weld interface showing the effects of the buttering at two different conditions: Buttering (Butt.) and multipass deposition (Dep.) welding at 25ºC and at 200-230ºC preheat/interpass temperature.
Right: Respective (0,2 kgf) microhardness.

4.2 Effects of the Post Welding Heat Treatment

After the PWHT all samples continued to show hard zones (arrows in fig. 6 and hardness values in table 5), although the distinct temperatures used had different consequences on the final joint microstructure. In samples treated at 420ºC a tempering of the PDZ and HAZ microstructures was verified: the lower temperature heating brought the better results in comparison with others PWHT temperatures, and a reduction of approximately 60 HV was observed in comparison to as-welded samples. Nevertheless a final hardness around 400 HV, after 3 hours heating, is still high, so that the practical effectiveness of this low temperature PWTH is questionable.

None hardness decrease at the PDZ was observed for PWHT at 540ºC and 660ºC (table 5). This could be the result of austenite formation at the high temperature heating and therefore "virgin" martensite appearance during the subsequent cooling, as interpreted by Kvaale *(2003).* In fact, as Ni lowers A_{c1} , for a PDZ with 87 % of base metal dilution (composition given in Table 2) austenite will be already stable for temperatures above approximately 500ºC (according to the following formula derived for 13%Cr steel). Besides that, in accordance to equation 3, derived for 13/4 Cr-Ni steels (Folkhard, *1988)*, martensite formation will start at temperature below 135ºC (± 20ºC).

$$A_{c1} = 723 - 25Mn - 30Ni + 25Si + 25Mo \quad {}^{o}C \tag{2}$$

$$M_S = 492 - 125C - 290Ni - 10Cr + 65.5Mn \quad {}^{o}C \tag{3}$$

For PWHT at 420º C, no transformable austenite is formed, so that this low temperature heat treatment is only sufficient to temper the previous existent martensite. After PWHT at 540ºC the highest hardness was measured; a peak value above 500 HV was observed (table 5), although by optical microscopy also no evidence of precipitation was verified. After thermal treatment at 660ºC the PDZ showed a dark etching, differently of the bright appearance of other samples. In this case decarburization and coarsening of ferrite grains along the fusion line in the CGHAZ were noted, as already reported by Kvaale *(2003)*, Omar *(1998)* and Pope *(2003).*

Table 5: Hardness values in HAZ and PDZ after PWHT at different temperatures:

PWHT Temperature	$HV_{(0.1)}$ PDZ	$HV_{(0.1)}$HAZ
As welded	475	334
420 º C	417	335
540 º C	513	334
660 º C	467	300

Font: Experimental procedure.

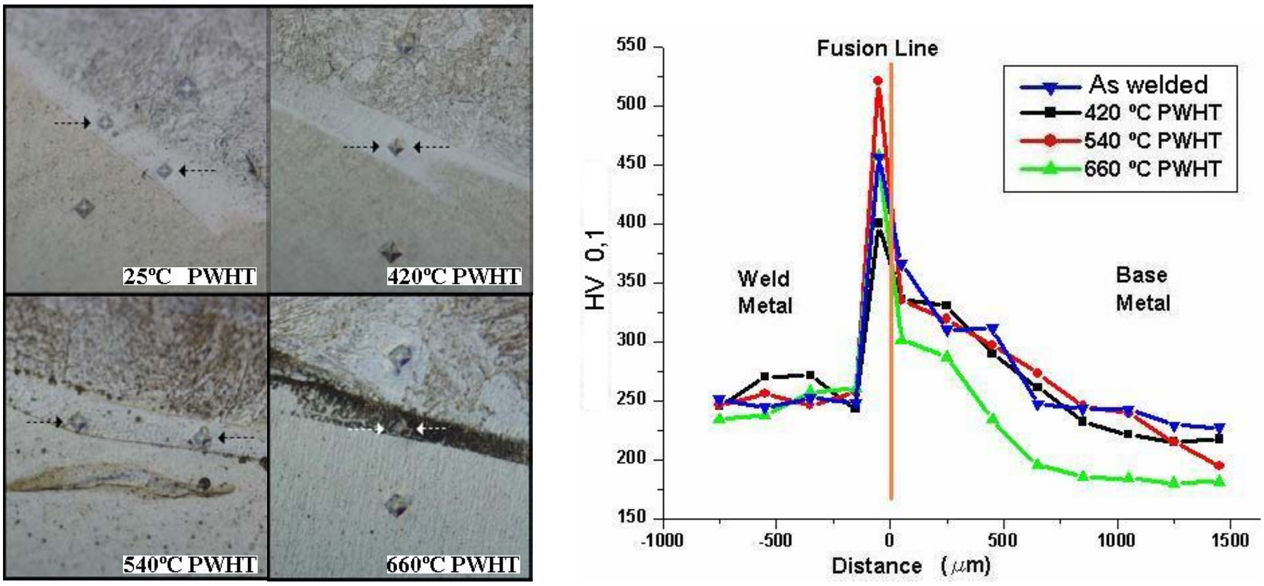

Figure 3: Weld interface showing the effects of different PWHT temperatures (500x). Right: 0,1 HV profiles.

5. Conclusions

API X-60 ferritic steel pipes when welded with nickel based filler metal may contain PDZs with martensitic microstructures and maximum hardness up to 450 HV localized along the fusion line mainly at the bottom of the first passes.

In order to minimize the formation of both PDZ and hard CG-HAZ, an adequate combination of welding energy and preheat temperature must be selected: low welding energy for the first passes of Inconel 625 implies in reduced base metal dilution and consequently lower is the carbon content in weld metal, diminishing the tendency towards hard martensite formation along the fusion line. However, low welding energy implies in high cooling rates (Δt 8-5 under 3s), what requires a minimum preheat necessary to suppress any martensitic transformation in CG-HAZ.

Buttering with E 9018-D1 prior to Inconel deposition is a positive alternative to promote a substratum with less carbon content. This way, higher is the base metal dilution that can be accommodated in weld metal for the same carbon concentration, also reducing the maximum hardness of possible martensitic microstructures formed along the weld interface.

Post welding heat treatments at higher temperatures (540 and 650 ºC) have detrimental effects and should be avoided. No hardness decrease until 3 hours heating. At 650ºC decarburization and ferrite grain growth occurs in coarsened grains heat affected zone (CGHAZ). During PWHT diffusion from the low alloy steel HAZ causes carbon enrichment in the PDZ. This tendency increases with the tempering temperature. At lower temperature (420 ºC) better results are observed, forming a softer tempered martensite in the PDZ.

6. Acknowledgements

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