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INFLUENCE OF PREHEAT AND POST WELDING HEAT TREATMENT ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF HIGH STRENGTH STEEL WELD METAL FOR APPLICATION IN MOORING COMPONENTS

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Abstract. *The present work is part of a research program for the development of welding procedures for components of mooring systems of oil platforms. In the specific case of the work in subject, the effect of varying the cooling rate of a high strength steel weld metal deposited by GMAW process is discussed for obtaining high mechanical strength and impact toughness, of the order of 860 MPa and 50 joules at –20°C, respectively. Welded joints by GMAW process were prepared using preheats of 150, 200 and 250°C. After welding, tensile, impact Charpy-V and hardness tests and metallographic examination by scanning electron microscopy were performed in specimens removed integrally from the weld metal, both in as welded and heat treated conditions. The post weld heat treatment (PWHT) was conducted at 600ºC for 1 hour. The results show that it is necessary to control the cooling rate to achieve the requirements of IACS W22 R4 Grade steel, mainly due to the reduction of ultimate tensile strength after post welding heat treatment, which is mandatory for this application for stress relieving.*

Keywords: *weld metal, mechanical properties, preheat, post weld heat treatment.*

1. INTRODUCTION

Mooring lines of offshore oil exploitation platforms for deep water consists of long lengths of steel chain links, wire ropes and other accessories (Costa, *et al.*, 2001; Paiva, 2000). Usually, these lines are designed for an operational life of about 20 years and periodic inspections are mandatory for monitoring the structural integrity of these components. The failure of a single element in a mooring line can promote incalculable environmental damage and severe economic losses. The adverse environment of the ocean and the loadings produced by the combination of the wind, waves and currents leads to a complex and alternate loading favoring the occurrence of fatigue failure and crack propagation (Kvitrud, 2014).

Based on this scenario, the standards for materials selection and application in mooring components, presents a set of very stringent requirements, such as ultimate tensile strength and impact toughness, of the order of 860 MPa and 50 joules at –20°C, respectively (IACS, 2011) for R4 grade steel. Particularly, for R4 grades and higher, it is important to take into account the necessity of welding, since it can represent an additional challenge, because even a consumable with the highest tensile strength qualified by AWS 5.5 (AWS 5.5., 1996), i.e., AWS E12018 (UTS = 830MPa), is not capable to achieve this requirement.

Also, it is important to observe that in this application, the need of post welding heat treatment is mandatory in order to reduce the residual stresses (Jorge, *et al.*, 2001, 2008; Pacheco, *et al.*, 2001). It generates an additional problem to be solved, becoming necessary to implement a special research program to evaluate the viability of using some commercial consumables for this application, which must be discussed by the classifying societies, suppliers and clients.

Some previous papers (Gomes, *et al.*, 2012, 2013; Jorge, *et al.*, 2007, 2008, 2013; Pacheco, 2001; Suman, *et al.*, 2004) have discussed the performance of weld metals deposited by SMAW process. Once the increasing in productivity needs to be considered, an extension of this program was developed for studying the mechanical properties of weld metals deposited by GMAW process, as well.

This work presents the results obtained from a study of the effect of cooling rate and post welding heat treatment on the mechanical properties of a high strength steel weld metal deposited by GMAW process used for welding of R4 Grade steel.

2. EXPERIMENTAL PROCEDURE

2.1 Consumables

The welding consumables employed were flux cored wires with 1.2mm diameter, according to the AWS 5.28 class ER 120S-G specification (AWS 5.28, 1996). The chemical composition of the deposited weld metal is showed in Tab. 1.

Table 1. Chemical composition of the deposited weld metals (wt. %).

Weld Metal	C	Si	P	S	Mn	Mo	Ni	Cr	Cu	V	Ceq(1)
A	0.087	0.,53	0.015	0.008	1.58	0.43	1.77	0.28	0.03	0.008	0.62
B	0.09	0.54	0.013	0.010	1.58	0.43	1.72	0.28	0.03	0.005	0.61
C	0.09	0.57	0.015	0.008	1.58	0.44	1.83	0.29	0.03	0.007	0.62

(1) $Ceq(_{IIW}) = C + Mn/6 + (Cr+Mo+V)/5 + (Cu+Ni)/15$

2.2 Welding

The joint geometry is illustrated in Fig.1. Welding was performed in the flat position by the GMAW process with preheats of 150, 200 and 250ºC, using the heat inputs and cooling times between 800 and 500^{0}C showed in Tab. 2. Cooling times were calculated for fill passes and top beads according to EN 1011-2 Annex D (EN 1011-2, 2003).

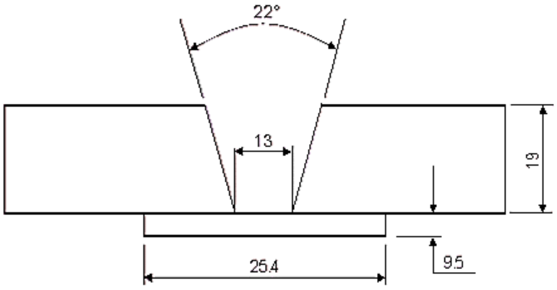


Figure 1. Weld joint geometry (mm).

Table 2. Nominal heat inputs and calculated cooling times.

Weld Metal	A	B	C
Preheat (ºC)	150	200	250
Nominal Heat Input (kJ/mm)	1.0	1.33	1.22
$\Delta t_{8/5}$ (fill passes), s	4.1	10.1	17.6
$\Delta t_{8/5}$ (top beads), s	3.9	10.3	10.4

2.3 Post Weld Heat Treatment (PWHT)

The weld deposits were tested in both conditions: as-welded and after post welding heat treatment (PWHT) performed at 600°C for 1 hour following air-cooling.

2.4 Metallographic Examination

Transverse sections were prepared and detailed examination by Scanning Electron Microscoppy (SEM) was carried out on top bead, columnar and reheated regions of the weld metal related to the Charpy-V notch position on the weld metals. The metallographic samples were carefully prepared using diamond paste as the polishing abrasive, etched with nital 2%. Additionally, quantitative analysis of microstructural constituents was performed by point to point counting technique using a 10x10 grid on the SEM screen. At least 1,000 points were counted as being statistically acceptable.

2.5 Mechanical Tests

Test pieces were removed for tension, impact Charpy-V and hardness tests, being its dimensions and test procedures in accordance to ASTM A-370 standard (ASTM, 2005). Tension tests at room temperature were performed on test specimens removed longitudinally to the weld metals (all weld metals). Charpy-V impact tests, at -40,–20 and 0ºC temperatures, were also performed on standard test pieces (10x10x55mm) removed transversally to the weld bead. The notch was positioned in the thickness section at position corresponding to the weld metal center line. The hardness test was performed on a test specimen transverse to the weld bead, using the Vickers scale with a load of 1 kgf.

3. RESULTS AND DISCUSSION

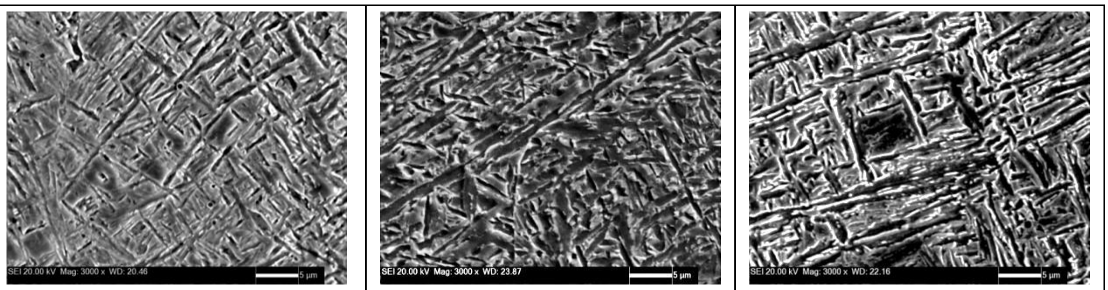
3.1 Metallographic Examination

A, B and C weld metals present a refined microstructure, consisting of a mixture of martensite and bainite, as it can be seen on Fig. 2 and 3. It is also observed the occurrence of a higher proportion of martensite at the region of the last pass concerning the filling passes, which can be attributed to the different cooling times (Tab. 3). These findings are in accordance with Lord, *et al*. (1999) who showed that small variations at cooling rates could promote great changes on microstructures of high strength steel weld metals.

Svensson (1999) showed that weld metals with yield strength (YS) of approximately 690 MPa, ultimate tensile strength (UTS) of around 900 MPa and chemical composition containing nickel, chromium and molybdenum, had a microstructure consisting basically of a mixture of acicular ferrite, bainite and martensite, whereas weld metals essentially comprising bainite and martensite, present YS of 900 MPa and UTS of about 1,000 MPa.

In agreement with this, Ramirez (2008) studying weld metals with carbon equivalent of 0.47% and higher, had observed an increasing volume fraction of lower temperature transformation products, including martensite. The author had also observed that weld metals with higher alloying additions did not retransform during reheating induced during multipass welding, being the microstructure of the reheated weld metal very similar to the microstructure of the as-deposited weld metal. In the same way, Lord, *et al*. (1999), studying high strength steel weld metals obtained by SMAW, observed a microstructure consisting of a mixture of martensite and bainite. The results obtained in the present work are in agreement with the above statements.

Finally, it is important to mention that, being the development of microstructure in a large extent controlled by the manganese content (Svensson, 1999), when its content is increased to a certain level, the hardenability is high enough to the occurrence of predominance of martensite on the top bead regions (Gomes, *et al*., 2013), as observed in the present work (Tab. 3).



Weld A ($\Delta t_{8/5}$ = 3,9s)	Weld B ($\Delta t_{8/5}$ = 10,3s)	Weld C ($\Delta t_{8/5}$ = 10,4s)

Figure 2. Microstructures of the top bead of the weld metals (SEM). Etching: nital 2%.

Table 3. Properties of the studied weld metals.

Weld Metal	Preheat (ºC)	HI(1) (kJ/mm)	Nominal $\Delta t_{8/5}$ (s)	$\Delta t_{8/5}$ (s) TB(2)	Martensite (%) TB(2) (%)	$\Delta t_{8/5}$ (s) FP(3)	Martensite (%) FP(3)
A	150	1.0	4.3	3.9	100	4.1	100
B	200	1.33	10.2	10.3	98	10.1	89
C	250	1.22	14.7	10.4	96	17.6	75

(1) Heat Input; (2) Top Beads; (3) Fill Passes.

3.2 Mechanical Tests

Table 4 shows the tensile tests results obtained from the weld deposits. It can be observed that higher UTS values are associated to higher volume fraction of martensite and lower cooling times in accordance to observed elsewhere (Karlsson, *et al*., 2004, Keehan, *et al*., 2010, Lord, *et al*., 1999, Ramirez, 2009).

In their works involving weld metals obtained by Shielded Metal Arc Welding (SMAW), Keehan, *et al*. (2010) have observed the reduction of Ultimate Tensile Strength (UTS) and impact toughness with increasing the cooling time ($\Delta t_{8/5}$). According to the authors, high UTS levels are associated to high martensite and bainite volumetric fractions, the same tendency observed in the present work.

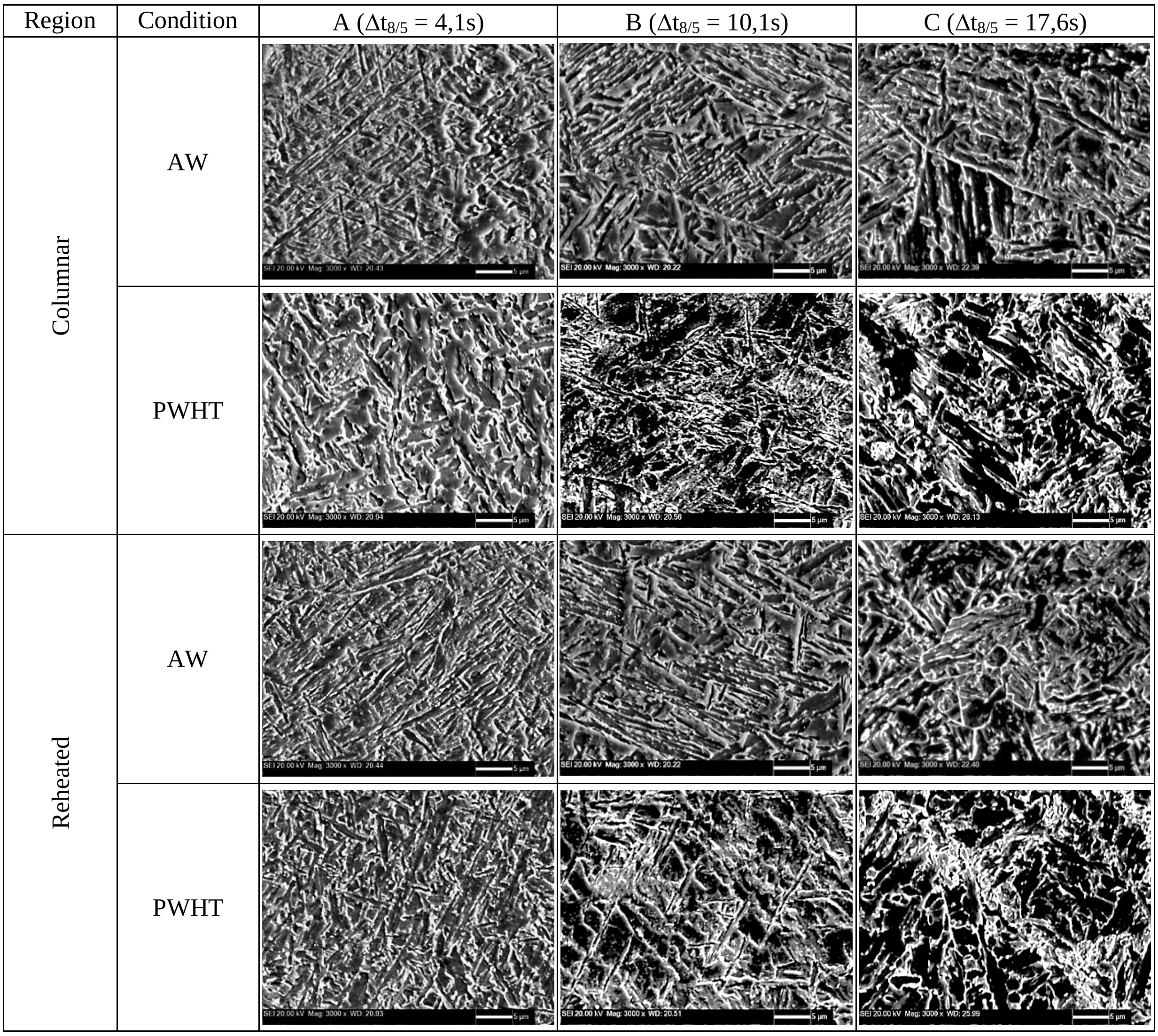


Figure 3. Microstructures of the columnar and reheated regions corresponding to Charpy-V notch positions of the weld metals (SEM). Etching: nital 2%.

PWHT promoted a reduction on the UTS for all conditions. In particular, for B and C weld metals, PWHT reduced the ultimate tensile strength to levels below the R4 grade steel requirements (IACS, 2011). According to Surian, *et al.* (2010), it is well known that when selecting a C-Mn steel as an alloy base, in order to increase tensile strength it becomes necessary adding to the alloy base alloying elements such as Ni, Mo, and/or Cr, which will modify other properties as well. It is also known that an increase of tensile strength is frequently accompanied by a loss in toughness, particularly at low temperatures.

For this reason, when designing an electrode formulation starting with C-Mn consumables, the main concern is devoted to maintaining the toughness requirements and the achievement of adequate tensile properties is seldom of concern. Consequently, it can promote some problems on present days to achieve the requirements for this property when working with high and extra high strength steel weld metals. In this respect, Surian, *et al.* (2010) observed that there is a narrow range of heat input within which mechanical property requirements were achieved.

Keehan, *et al.* (2010), found similar conclusions where it was observed that, although strength decreases with increasing cooling time, there was an operational window for Δt8/5 of about 3 to 13s within which high strength and good toughness could be achieved. According to the authors, this is not a limitation in behavior, as welding procedures resulting in extreme cooling rates are rarely desirable. The most practical concern is that transformation behavior and properties in real weldments are always affected by dilution. Considering this aspect, it is expected an increase on UTS for real weldments (Jorge, 2001; Sumam, 2004).

Finally, it was observed that to reach the minimum requirement for R4 grade steel after PWHT, it is necessary strict control of the cooling rate.

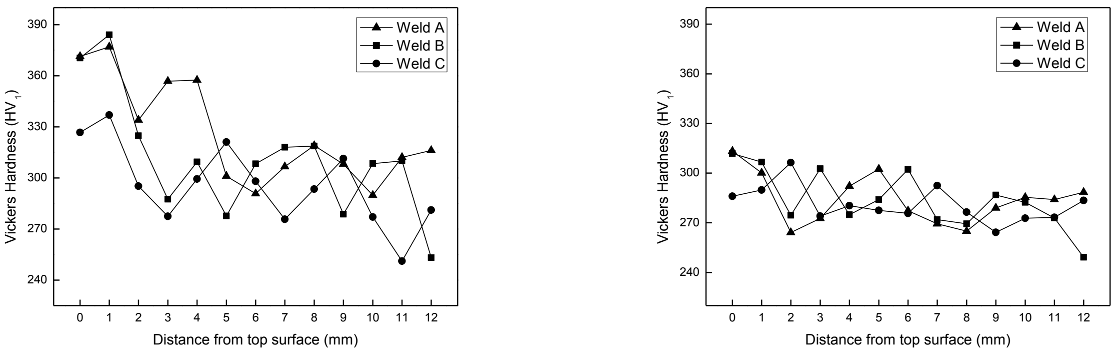
Table 4. Results of tensile tests.

Weld metal	Condition	YS[1] (MPa)	UTS[2] (MPa)	El[3] (%)	RA[4] (%)
A	As- welded	939	962	13	56
	PWHT	829	881	16	57
B	As- welded	774	875	18	64
	PWHT	774	841	16	52
C	As- welded	815	864	19	64
	PWHT	729	815	22	65
Required (IACS, 2011)		*580*	*860*	*12*	*50*

[1] Yield Strength; [2] Ultimate Tensile Strength; [3] Elongation; [4] Reduction of Area.

Figure 4 shows the results of Vickers hardness tests of the weld metals. As expected, the hardness presents the same tendency of the UTS. It can be noted that the weld metal A presented the highest values whereas the lowest ones were provided by the weld metal C. In addition, it can be seen that the region near to the top surface presented higher hardness values, in agreement to the microstructures observed.

The PWHT promoted a reduction on the hardness results (Fig. 9), as consequence of tempering of the microstructure mainly at the region of the last passes.

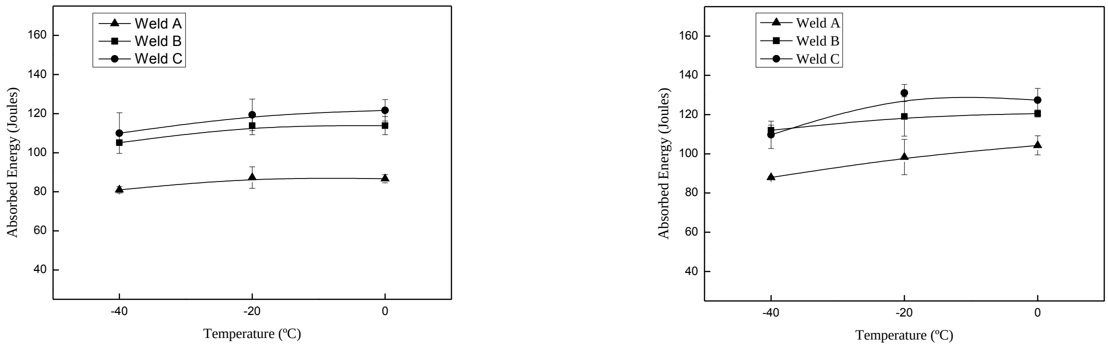


As welded PWHT

Figure 4. Results of hardness tests.

Figure 5 shows the results of Charpy-V impact tests, where it can be noted that the PWHT promoted a small improvement to the impact toughness for all weld metals. This improvement can be attributed to the tempering of the microstructure.

Of the greatest importance is the fact that, for all conditions, the results are always much higher than the minimum of 36 Joules (IACS, 2011) required for R4 steel grade steel (Fig.5).



As welded PWHT

Figure 5. Results of Charpy-V impact tests.

4. CONCLUSIONS

Based on the aspects discussed in the present work, the main conclusions are:

a) High strength steel weld metals performed by GMAW are capable to reach high mechanical strength and impact toughness, of the order of 860 MPa and 50 Joules at -20 ºC, respectively;
b) PWHT promoted a reduction on UTS and an improvement on impact toughness due to the tempering of the microstructure and;
c) Strict control of the cooling rate is necessary to reach the minimum requirement for R4 grade steel after PWHT.

5. ACKNOWLEDGEMENTS

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