



## WET UNDERWATER WELDING OF C-MN STEEL USING FCAW PROCESS

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**Abstract.** *The need of investigation on the subject of mechanised wet welding has been continuously addressed by different researchers and required by the industrial sector. The spectrum of application of such research is wide: oil and gas industry, maritime-insurance companies and shipyards can achieve fast delivery repair and fabrication by using wet welding. Also cost reduction on the process can be achieved by switching from covered electrodes to flux-cored wires. In underwater welding, C-Mn steels are largely used and the procedures are normally carried out on horizontal position. Therefore, this paper details the parameter selection, welding and procedure qualification for butt and fillet welds on horizontal position, according to AWS D3.6M – Class A. Both S275 and S355 C-Mn steels were used to cover a wide range of CE (0.36 and 0.42, respectively). The flux-cored wire was PPS-AN1, with 1.6 mm of diameter. Experiments were carried out in a 1x1x1m water tank in fresh water at 9 °C and at ~0.5m water depth, which allows qualification for water depths of 0.5 to 10.5 m. A conventional flat (voltage-current) characteristic power source was used. For the mechanised welds, the torch was mounted on one-axis mechanised horizontal traverse. Electrical signals for current and voltage were acquired at 1 kHz per channel by appropriated instrumentation. Firstly a total of 84 BOP (bead on plate) trials were carried out to identify the parameters in downhand (PA/1G) and horizontal (PC/2G) positions. The optimum parameter selection was identified by using statistical design and the final set of parameters is voltage at 30 V; 4-m/min WFS; 20-cm/min TS; 90° of leading angle; 15° of working angle; inductance at 50% and 15-mm contact-tip-to-work distance. Using these parameters, the welding procedure was carried out following AWS D3.6M in horizontal position for fillet (PB/2F) and butt (PC/2G) welds, using the two C-Mn steels. The set of coupons comprise, besides butt welds and fillet welds, all-weld-metal and transverse/longitudinal shear strength plates. The plate thickness for butt welds is 10 mm and for fillet ones is 25 mm. After the welding, the plate sets were delivery to inspection for independent evaluation. The results indicate the reaching Class B for fillet welds and Class C for butt welds. The specific conclusions are radiography and macroetches show slag-entrapment issues; the weld metal provided good impact test results; wire with good slag detachability in downhand position, but very poor in horizontal position; successful results were obtained for both transverse and longitudinal shear strength coupons.*

**Keywords:** *Brazing, exploration, oil wells, Destruction, Crushed carbide*

### 1. INTRODUCTION

Self-shielded FCAW for wet welding has proved all its potentiality, but in terms of technological application there is still a lack of use and a lot of field work to be carried out (Vilarinho and Raghunathan, 2009). In fact, potential savings from use of FCA welding operations against covered-electrode process and also against hyperbaric welding could go up to 50%. This opens a huge horizon for R&D&I for the process. Therefore, the need of further investigation on the subject of mechanised wet welding was addressed. Important cost reduction on the process can be achieved by switching from covered electrodes to flux-cored wires. The spectrum of application of such research is very wide. Oil and gas industry, maritime-insurance companies and shipyards can achieve fast delivery repair and fabrication by using wet welding, instead of dry underwater and conventional (not underwater) ones

The standard that rules the underwater welding is the AWS D3.6M (1999). Although some criticism is presented in literature for this standard (especially because the long time without reviews), on the author's view it is a very straightforward standard to follow with reasonable requirements. Nevertheless, updates are normally healthy for the continuous development of any standard, which could be further addressed with other research project. The AWS D3.6M divides the quality of the weldments in classes, which top class is Class A.

The main differences on required tests between Class A and B is the All-Weld-Metal requirements for Class A, which do not exist for Class B, the need of impact and radiography for weld metal in fillet weld, the bend radius (from 2T up to 3-1/3T for Class A and 6T for Class B), the maximum micro-hardness (325HV10 for Class A against 375HV10 for Class B).

Concerning acceptance criteria, the examination requirements for Class A are slightly more severe than the ones for Class B. Both are based on the non-existence of cracks and the size of slag and porosity, as well as the dimension of

L. O. Vilarinho, W. Lucas and S. Raghunathan  
Wet Underwater Welding of C-Mn Steel Using FCAW Process

undercut. Class A requires complete fusion, whereas Class B allows incomplete fusion. The desirable, acceptable and unacceptable weld profiles have lower tolerance for Class A, but the shapes are the same for Class B (small convexity for fillet welds and small reinforcement for groove welds).

Concerning base materials for welding, in underwater welding, C-Mn steels are largely used and the procedures are normally carried out on horizontal position. IIW carbon-equivalent (CE) for these steels varies from 0.35 to 0.45, whereas the AWS D3.6M does not recommend CE over 0.40.

Therefore, basing on these ideas, this paper details the parameter selection, welding and procedure qualification for butt and fillet welds on horizontal position, according to AWS D3.6M – Class A. Both S275 and S355 C-Mn steels were used to cover a wide range of CE (0.36 and 0.42, respectively). The flux-cored wire was developed by The E O Paton Welding Institute and it is designed as PPS-AN1, with 1.6 mm of diameter

## 2. EXPERIMENTAL APPROACH

Experiments were carried out in a 1x1x1m water tank (Fig. 1 and Fig. 2) in fresh water at 9 °C and at ~0.5m water depth, which allows qualification for water depths of 0.5 to 10.5m (AWS D3.6M, 1999). A conventional flat (voltage-current) characteristic power source was used. For the mechanised welds, the torch was mounted on one-axis mechanised horizontal traverse. Electrical signals for current and voltage were acquired at 1 kHz per channel by appropriated instrumentation.



Figure 1. Experimental rig



Figure 2. First view of the underwater initial trials in horizontal position

The flux-cored wire (Paton PPS-AN1, with 1.6 mm of diameter) composition is shown on Tab. 1, together with the all plates employed for both C-Mn steels: S275 and S355, with average CE (carbon equivalent) equal to 0.36 and 0.42, respectively.

Firstly a total of 84 BOP (bead on plate) trials were carried out to identify the parameters in downhand (PA/1G) and horizontal (PC/2G) positions. The optimum parameter selection was identified by refining the 84 runs by using statistical design (Tab. 2) and the final set of parameters is voltage at 30 V; 4-m/min WFS; 20-cm/min TS; 90° of leading angle; 15° of working angle; inductance at 50% and 15-mm contact-tip-to-work distance.

Using these parameters, the welding procedure was carried out following AWS D3.6M in horizontal position for fillet (PB/2F) and butt (PC/2G) welds, using the two C-Mn steels. The set of coupons comprise, besides butt welds and fillet welds, all-weld-metal and transverse/longitudinal shear strength plates, as shown in Figs. 3 and 4. The plate thickness for butt welds is 10 mm and for fillet ones is 25 mm. After the welding, the plate sets were assessed by independent inspection.

Table 1. Chemical analyses and C.E. calculation from TWI Report Ns. S/09/50, S/09/66 and S/99/287

Material	Thickness [mm]	C	Si	Mn	P	S	Cr	Mo	Ni	Ti	V	Al	Cu	C.E.
S275	25	0.15	0.21	1.18	0.026	0.013	0.046	0.006	0.026	0.001	0.002	0.028	0.021	0.361
S275	12.5	0.14	0.19	1.16	0.016	0.014	0.017	0.003	0.018	0.001	0.002	0.030	0.023	0.340
S355	12.5	0.16	0.25	1.53	0.020	0.023	0.014	0.003	0.029	0.001	0.003	0.030	0.019	0.422
S275	20	0.18	0.37	1.17	0.013	0.011	0.010	0.003	0.020	0.001	0.001	0.003	0.011	0.380
S355	20	0.14	0.30	1.41	0.013	0.015	0.016	0.004	0.026	0.001	0.046	0.027	0.032	0.392
S355	25	0.16	0.21	1.42	0.017	0.002	0.018	0.003	0.015	0.003	0.002	0.031	0.014	0.403
S275	10	0.17	0.26	1.09	0.019	0.014	0.028	0.003	0.020	0.002	0.003	0.049	0.022	0.361
S355	10	0.17	0.32	1.57	0.014	0.004	0.022	0.004	0.009	0.004	0.002	0.022	0.023	0.439
PWI wire*	-	0.03	0.005	0.11	0.031	0.018	0.03	0.006	1.7	0.002	0.001	0.003	0.07	0.174

\* From the weld metal.

Table 2. Central Composite Design experimental design

Run	Voltage [V]	WFS [m/min]	TS [cm/min]	Vmean [V]	Vrms [V]	Imean [A]	Irms [A]
L01	26	3	10	25.509	25.983	139.15	151.37
L02	26	3	20	25.486	25.821	141.56	150.41
L03	26	5	10	24.972	25.432	216.73	229.09
L04	26	5	20	24.996	25.306	207.97	216.87
L05	30	3	10	29.602	30.218	138.47	147.60
L06	30	3	20	29.764	30.635	139.26	148.87
L07	30	5	10	29.297	29.612	215.10	222.25
L08	30	5	20	29.293	29.640	212.44	219.60
L09	26	4	15	25.462	25.838	180.77	187.36
L10	30	4	15	29.361	29.693	187.37	193.60
L11	28	3	15	27.540	27.975	139.78	148.49
L12	28	5	15	27.297	27.686	211.80	218.02
L13	28	4	10	27.299	27.581	179.40	187.30
L14	28	4	20	27.303	27.540	179.46	186.05
L15	28	4	15	27.151	27.403	180.25	187.15
L16	28	4	15	27.240	27.479	180.47	186.76

WFS: Wire feed speed; TS: Travel speed; Vmean: average voltage; Vrms: rms voltage; Imean: average current; Irms: rms current.

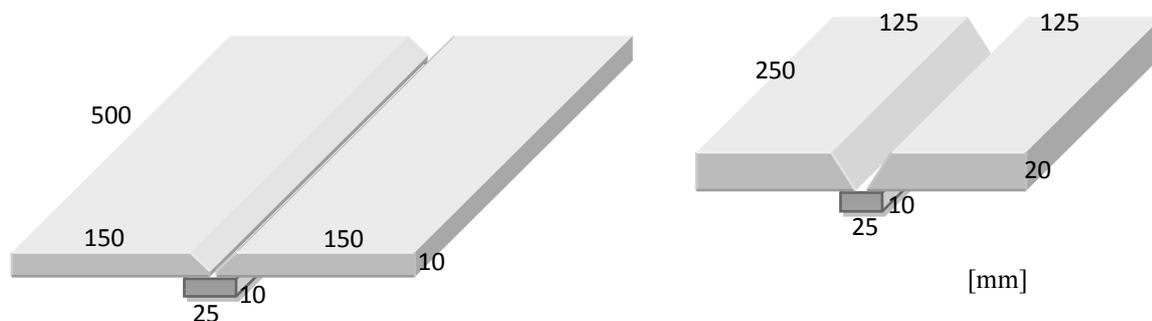


Figure 3. Required coupons for butt weld procedure qualification: plate test (left) and all-weld metal (right)

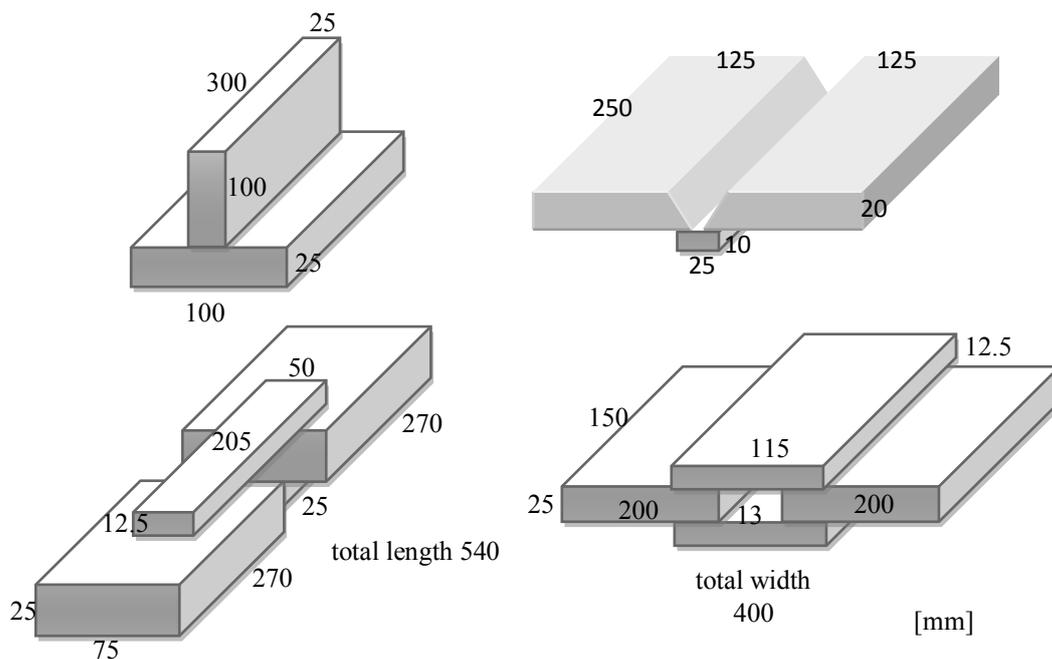


Figure 4. Required coupons for fillet weld procedure qualification: plate test (upper left), all-weld metal plate (upper right), longitudinal shear test (lower left) and transverse shear test (lower right)

### 3. RESULTS AND DISCUSSION

#### 3.1 5.1 Initial trials on bead-on-plate

The final beads from the statistical experimental design are shown in Fig. 5, just after welding (left images) and after manual brushing (right). The importance of keeping the brushing manual is to assess the slag detachability. In this case of flat position, the slag presents a very good detachability.

Examples of the recorded electrical signals are shown in Figs. 6 and 7. These two figures represent process where there were more (Fig. 6) and less (Fig. 7) fluctuation observed during the welding, what can be verified by the voltage fluctuation (although the static characteristic of the power source is constant voltage).

After the manual brushing of the weld beads, four Welding Engineers at TWI assessed them basing on visual appearance a stability index was created by analysing the voltage signal, since Figs. 6 and 7 show that there is more or less voltage fluctuation according to the parameters selection. Therefore, it is proposed here an index based on Eq. (1), which can be straight implemented as an algorithm in any software and the lower the index, the higher the process stability. By crossing the visual analysis and the index results (Tab. 3), it is possible to conclude that the lower the index, the better is the bead quality.

$$\text{Index} = \frac{\text{Number of points where } V_i \geq V_{cut} \cdot \frac{V_{ref\_min}}{V_{ref}}}{\text{Total number of points}} \quad (1)$$

where,  $V_i$  is the voltage values acquired;  $V_{cut}$  is the voltage level above which is instability is considered;  $V_{ref\_min}$  is the minimum reference voltage set in all the experiments (in this case 26 V) and  $V_{ref}$  is the reference voltage for the run from which the index is being calculated. The reason for the correction suggested as  $V_{ref\_min}/V_{ref}$  is due to the fact that higher references voltages naturally produce higher voltage levels that can overcome  $V_{cut}$ , but not necessarily meaning higher instability.

Using the gathered data from the experimental matrix, the index was calculated for each run and it is shown in Tab. 3. Three different levels of  $V_{cut}$  were selected: 45, 50 and 60 V. Moreover, it was also included in the index before and after the suggested correction ( $V_{ref\_min}/V_{ref}$ ), so its importance could be notice. The trends of Tab. 4 are better visualised in Fig. 8. Using the previous knowledge from the welding engineers it is expected that the best bead is the L15, which indeed has one of the lowest indexes.

It is important to mention that large volume of spattering was noticed. During the experiments, spatter were collected and for a 31.9 g of deposited material (calculated from the linear density of the wire, measured by a precision scale, and welding time), 9.8 g was lost in the spattering form (collected and measured by a precision scale). This means that ~30% of the wire mass was lost.



Figure 5. Bead appearance just after welding (left) and after manual brushing (right) for L01 to L16 runs

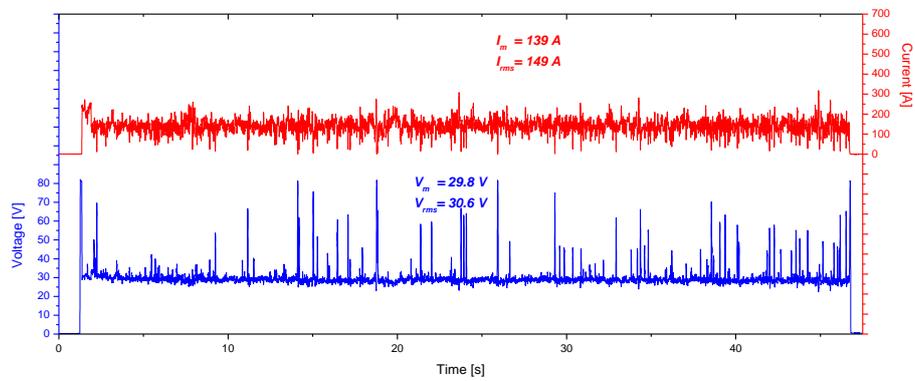


Figure 6. Electrical signals for the run L06

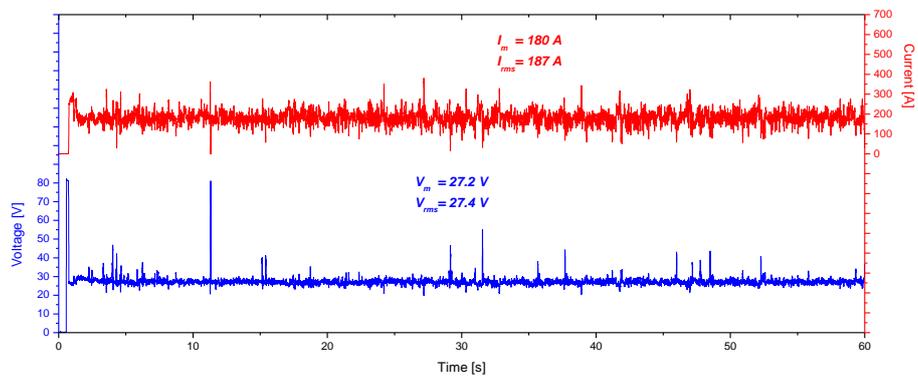


Figure 7. Electrical signals for run L15

Table 3. Results for CCD experimental design in terms of indexes

Run	Index45	Index45Corr	Index50	Index50Corr	Index60	Index60Corr
L01	0.582	0.582	0.365	0.365	0.222	0.222
L02	0.421	0.421	0.327	0.327	0.299	0.299
L03	0.547	0.547	0.361	0.361	0.190	0.190
L04	0.788	0.788	0.707	0.707	0.667	0.667
L05	1.968	1.705	1.520	1.317	1.135	0.984
L06	2.235	1.937	1.960	1.698	1.674	1.450
L07	0.657	0.570	0.500	0.433	0.365	0.316
L08	0.708	0.614	0.559	0.485	0.494	0.428
L09	0.448	0.448	0.387	0.387	0.335	0.335
L10	0.691	0.598	0.577	0.500	0.469	0.407
L11	0.766	0.712	0.596	0.554	0.503	0.467
L12	0.660	0.613	0.555	0.515	0.490	0.455
L13	0.468	0.435	0.312	0.289	0.192	0.178
L14	0.320	0.297	0.285	0.265	0.225	0.209
L15	0.329	0.306	0.282	0.262	0.204	0.189
L16	0.372	0.346	0.273	0.253	0.185	0.172

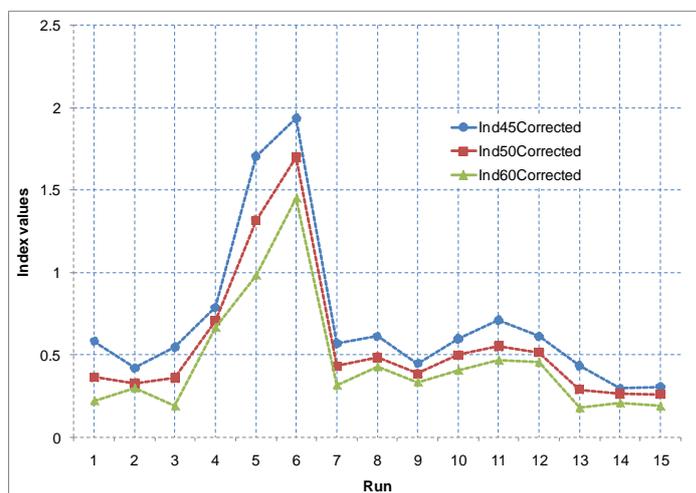


Figure 8. Comparison for the indexes with different voltages as reference

Further runs were also conducted varying working/leading angles, inductance and CTWD (contact tip to workpiece distance). They were carried out on a trial-and-error basis, bead after bead, so the researcher defined the best following steps to proceed, basing on his experience. At the end, the final set of parameters to be employed on the welding procedure is voltage at 30 V; 4-m/min WFS; 20-cm/min TS; 90° of leading angle; 15° of working angle; inductance at 50% and 15-mm CTWD.

At the end a total of 84 beads were made (including previous beads). It must be pointed out that one main feature noted was that the beads presented very good slag detachability in downhand (flat) position. However, the beads deposited in horizontal position required much more effort for slag removal.

### 3.2 Butt weld qualification

From the parameter set obtained from BOP deposits on PC(2G) position, butt weld procedure was carried out following the AWS D3.6M, Class A requirements. For the qualification of butt welds, both butt weld with V groove set and all-weld-metal set are required. An example of the final filled joints is shown in Fig. 9 for butt welds of S275 steel. After independent inspection, Tab. 9 brings the summary of the qualification results. As an example of the radiographic films, Fig. 10 presents the result for the S275 butt weld. The final macrographs are shown in Fig. 11.

The results also showed that all-weld-metal impact (Charpy) test successfully overcame the limit of 20 J. The main point here is the temperature selected as 0 °C, whereas -20 °C is more frequently used. In any case, the high Ni content (1.7% according to chemical analyses on Tab. 1) is the main responsible for this achievement. It must be pointed out that the impact test results cannot be promptly compared to D3.6M, because the employed specimens were reduced size (10 x 5 mm), instead of full size (10 x 10 mm). According to ASTM A370-07a (2007), the energy of a 10 x 5 mm

specimen is half of the value required for a full-size one. Therefore, since a minimum of 19 J and an average of 27 J are required by the D3.6M, these values become 10 J and 14 J, respectively, i.e., the achieved toughness is qualified.

Although the impact results were very good, probably because of the high Ni content in the wire (Tab. 1), the other results were very poor, specially the bending ones for the weld metal. This could be the effect of the slag entrapment (Fig. 12). Also, the UTS (ultimate tension strength) results showed that the wire has a low mechanical resistance. This is mainly due to its low CE, which could be coped with alloying elements, especially Nb. Since the stress concentration factor, naturally introduced by arc welding in any joining; the process requires a wire with higher mechanical resistance than compared to the base metal. Therefore, the all-weld-metal set for the S355 steel is approved and the S275 is not.



Figure 9. Butt weld for S275 steel



Figure 10. X-ray result for butt weld for S275 steel

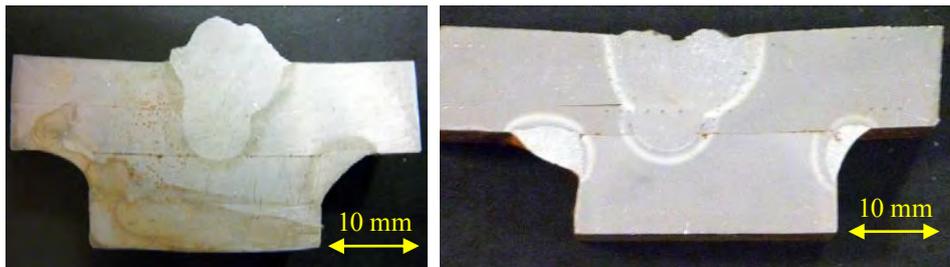


Figure 11. Macrographs for butt welds for S275 steel (left) and S355 steel (right)

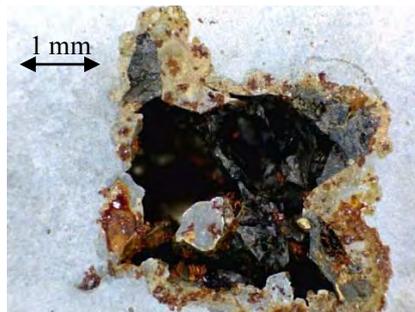


Figure 12. Detail of slag entrapment on the all-weld-metal macroetch of S355 plate

### 3.3 Fillet Weld Qualification

Following the qualification requirements for Class A on the AWS D3.6M, the analysis for the all-weld-metal is the same carried out for the butt welds in the previous section. Examples of the welds are shown in Fig. 13, whereas Fig. 14 presents the obtained macrographes.



(a)



(b)



(c)

Figure 13. Examples of fillet welds obtained according to the coupons in Fig. 4

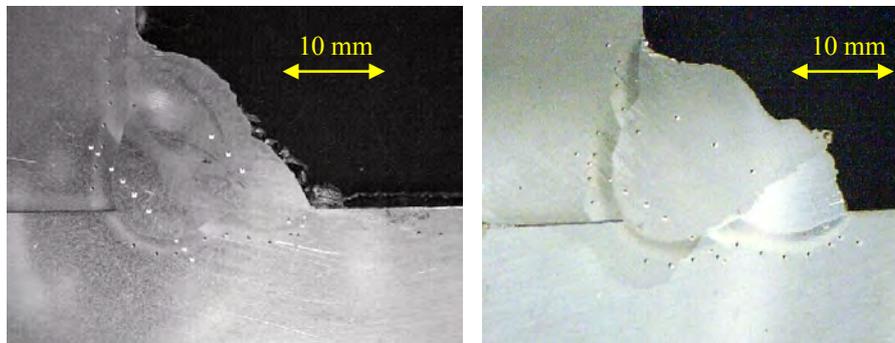


Figure 14. Macrographs for fillet welds for S275 steel (left) and S355 steel (right)

Fillet welds presented high micro-hardness values, following the trend of the butt welds. The test break revealed lack of penetration on root side, which is not tolerable by Class A (Class B accepts). This is an indicative that higher heat input must be used, which also could promote slower cooling rate and, therefore, reducing the hardness and crack possibility. The macros for the fillet welds (Fig. 14) did not show significant defects.

Finally both transverse and longitudinal shear strength coupons successfully qualified. This is a very good indicative that the high mechanical strength of the overall joint, capable of sustaining loads as much as in not-underwater welding.

#### 4. CONCLUSIONS

The employed strategy to qualify C-Mn steels with different CE for underwater welding failed to reach Class A. However, it demonstrated good indicatives for reaching Class B for fillet welds and Class C for butt welds. The specific conclusions are:

- Radiography and macroetches show slag-entrapment issues;
- The weld metal provided good impact test results, but low UTS, probably due to its high Ni content and low CE;
- Wire with good slag detachability in downhand position, but very poor in horizontal position;
- Successful results were obtained for both transverse and longitudinal shear strength coupons.

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