CONSUMABLES FOR WELDING OF (VERY) HIGH STRENGTH STEELS - MECHANICAL PROPERTIES OF WELDMENTS IN AS-WELDED AND STRESS-RELIEVED APPLICATIONS

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ABSTRACT

The use of (very) high strength steels for the design of high performance steel structures is highly promising as they can allow for substantial savings due to the thickness reduction of structural parts. The application of these steels for structural design, however, is not yet fully developed as limitations are imposed by design codes currently in effect. In addition, when welding is involved during fabrication, deterioration of the properties of these materials may occur. As an example, welding of high strength steels can induce a loss in toughness both in the material heat affected zone and in the weld metal, depending on the welding process, the welding consumable and the welding procedure, with respect to the base material chemical composition. Also, when a post weld heat treatment (PWHT) needs to be applied for certain applications, a change in the weldment properties takes place, what may appear as another limiting factor. For these reasons recommendations on the welding of high strength steel structures are needed for the steel and welding communities, as well as for fabricators. This paper provides several examples of mechanical properties obtained on various welded joints performed on high strength steels over 690MPa.

As a first example, Air Liquide Welding participated to the European collaborative research program ECOPRESS, which ran until 2002. One of the goals of this project consisted in extending the use of modern high strength steels for the construction of pressure vessels. The use of high strength steels would enable substantial savings without a loss on security for such applications, in comparison with current practice which utilizes steels of lower yield strengths. Amongst the different steels studied throughout the development of the project, the P690 steels were studied, for which welding solutions have been investigated. The paper outlines the strategy followed to develop submerged arc welding (SAW) and shielded metal arc welding (SMAW) consumables dedicated to the welding of these steels. All-weld-metal characterization results are provided, together with results obtained on joints carried out on the base material, both in the as-welded condition and after a PWHT, this latter often being unavoidable in the fabrication of pressure vessels. The influence of the base metal dilution and the welding procedure upon toughness and tensile properties is discussed, while an overmatched weld metal is looked for.

Secondly, various welding solutions have been developed for steels ranging from 690 through 1100MPa within the Air Liquide Welding group. Results obtained on parent materials for various welding processes (SMAW, SAW and FCAW – flux-cored arc welding) and types of assemblies were obtained and are reviewed in the paper.

Lastly, construction rules often recommend that the weld metal yield strength should be higher than that of the base metal, which is called the “overmatching”. A discussion is provided as to the need and possibility to satisfy or not the “overmatching” criterion in the weld metal compared to the steel properties.

KEYWORDS
High strength steel, structural steel, post weld heat treatment, welding consumables, overmatching

INTRODUCTION

High strength steels of up to about 500MPa have been used successfully over the last years for applications involving structural steel welding ; these include for instance pressure vessels, off-shore construction, bridges, cranes, ships, load-carrying vehicles and equipment…The actual trend is therefore an increasing interest in the use of higher strength steels (i.e. 690MPa and over), enabling a further increase in the strength to weight ratio and associated savings in materials, transportation and manufacturing costs. In spite of their high potential to fabricate high performance structures, the usage of high strength steels ranging from 690 and 1100MPa, which are commercially available steel grades, is in fact seriously limited by structural design codes and standards. Very high strength steels are indeed characterized by semi-empirical design concepts including Y/T, the yield to tensile strength ratio, and codes often call for the exclusion of these steels for structural applications when Y/T is superior to a certain value [Ref. 1]. This value can vary from 0.7 to 0.93 depending on the code / standard to be followed (both onshore and offshore). These restrictions apply to make sure enough ductility is guaranteed in the structure and brittle failure can not occur during service, even though real toughness data are not considered. For instance, the maximum allowable Y/T value is 0.85 for off-shore design requirements. As seen in Figure 1, most steels over 500MPa feature a Y/T ratio above the maximum value.

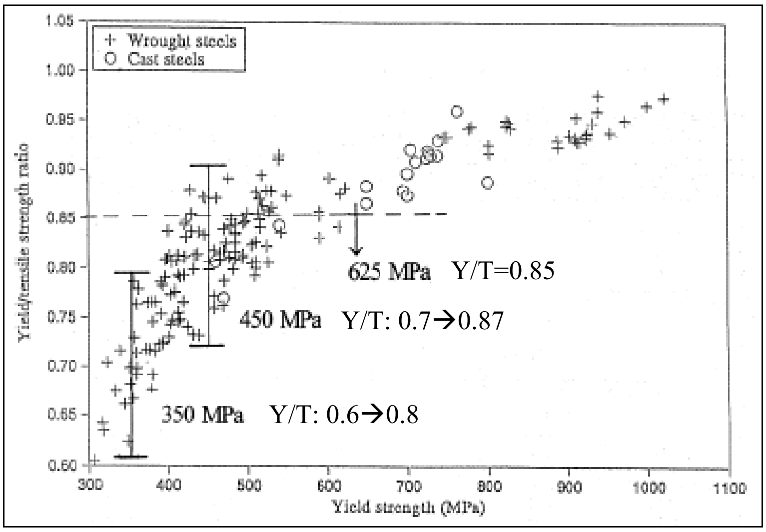

Figure 1: Yield / tensile ratios of a database of steel in the 300-1100MPa strength range [Ref. 1].

As an other example, the allowed design stress used to design a pressure vessels, f, is calculated as the minimum value amongst R_{eH}, $R_{P0,2}$ /1,5 and R_m /2,4 [Ref. 2]. Data given in Table 1 show that results of all three calculations are very similar for steels up to P265. For steels starting from 460MPa, however, the allowed design stress is imposed by Rm (again due to a higher Y/T value), what significantly reduces the interest for these steels for pressure vessels construction.

Table 1: Allowed design stress for various steel grades [Ref. 2].

Steel Grade	Nominal Yield Stress R_{eH}	Nominal Tensile Strength Rm	Allowed design stress based on $R_{P0,2}$ /1,5	Allowed design stress based on R_m / 2,4
P265	265	410	177	171
P355	355	510	236	213
P460	460	610	306	254
P690	690	800	460	320

As such, better knowledge of the behavior and implementation of these steels is still needed and efforts are necessary to propose consumables and solutions to efficiently weld these materials without a loss on security. Such knowledge would then help modify some criteria proposed by actual codes and regulations or simply practices based on steels of lower yield strength (mainly used as yet). In the present paper, a review of characterization results obtained with welding consumables from the Air Liquide Welding group and dedicated to high strength steels starting from 690MPa grades, are presented in a aim to provide recommendations to the steel and welding communities.

1. RESULTS ON 690MPA STEELS

One of the tasks of Air Liquide in the ECOPRESS program was to optimize weld metal for the P690 steel, with the aim to provide data to prove the high potential of high strength steels to reduce costs for pressure vessels construction, providing the safety factor applied on tensile strength would be modified {Refs. 1-2]. Thus, weld metals deposited using the submerged arc (SAW) and the shielding metal arc welding (SMAW) processes were tested with and without a stress relieving post weld heat treatment (PWHT).

1.1 DEVELOPMENT FOR SUBMERGED ARC WELDING OF 690MPA STEELS

An optimization was done using a Ø3.2mm flux-cored wire in combination with the high basic flux OP 121TT/W[1]. Welding parameters were 42cm/min travel speed, 1.9m/min wire feed rate, 29V, 525A DC+, heat input of 21.8kJ/cm and interpass temperature of 150°C. In the macro section showing the bead sequence in the joint on Figure 2, the areas of the weld metal affected by a subsequent deposited weld bead (reheated areas) and not affected areas (as-solidified areas) can be distinguished.

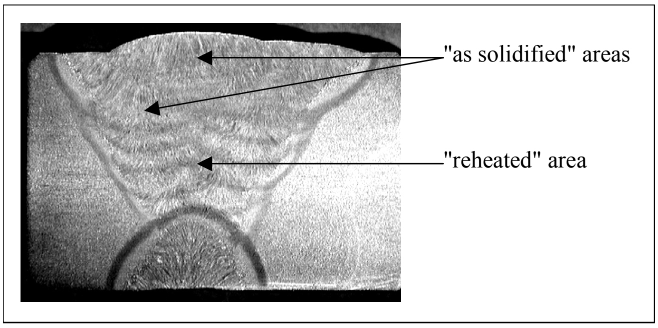

Figure 2: Macrography of a joint welded with flux-cored wire MOD 78 / flux OP 121TT/W in P690 steel (60° V-groove, 30mm thickness).

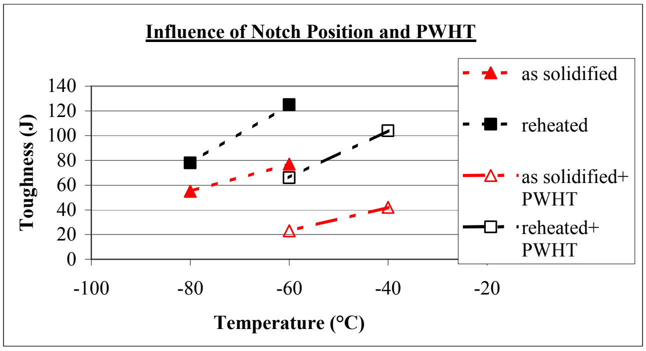

Figure 3: Influence of the notch position of the Charpy-V specimens in pure weld metal of flux-cored wire MOD 78 / OP 121TT/W after a PWHT of 580°C/3h.

The tempering induced by the following adjacent weld pass causes a microstructure refinement in the reheated areas. This structural change has a pronounced effect on toughness. If the notch of the Charpy-V sample is mainly positioned in the reheated areas, then the absorbed energy is higher than the energy absorbed when the notch is located in the as-solidified areas. The differences persist after a stress relieving heat treatment, Figure 3. In contrast, as the section of the tensile specimen covers a wide zone, no differentiation is possible between as-solidified and reheated areas.

[1] The letter "W" behind the common flux name OP 121TT indicates that selected batches of raw materials with extra low levels of phosphorus and sulphur were used.

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1.1.1. SAW P690 PURE WELD METAL

Data in Tables 2 and 3 show how mechanical properties are dependent upon weldment chemical compositions. Main conclusions are as follows:

- Low Oxygen content is favorable for good toughness in the as-welded condition as well as in the stress-relieved condition.
- Low Carbon / high Nickel seems to be more favorable to toughness than high Carbon / low Nickel (MOD 76B vs. MOD 76 formula).
- A PWHT of 580°C/3h induces a drop in tensile properties of about 30MPa and a reduction in toughness by 30-50%, in comparison with values obtained in the as-welded condition.
- After PWHT, formula MOD 76B exhibits better toughness than MOD 78, which is attributed to a more favorable balance of Si / Mn / Cr / Mo.

Table 2: Chemical composition of SAW welds of flux-cored wires with OP 121TT/W.

Formula	CB 9	CB 10	MOD 76	MOD 76B	MOD 78
% C	0.067	0.087	0.078	0.059	0.062
% Si	0.27	0.32	0.40	0.36	0.31
% Mn	1.5	1.68	1.54	1.58	1.43
% Cr	0.32	0.31	0.26	0.47	0.36
% Mo	0.51	0.52	0.47	0.36	0.44
% Ni	2.36	2.33	2.06	2.5	2.62
O / N (ppm)	330 / 41	310 / 34	240 / 39	270 / 50	280 / 49

Table 3: Mechanical properties in as solidified and reheated areas of the pure weld metals given in Table 2. Note: for toughness, "as" corresponds to the as solidified area, "rh" to the reheated area.

Formula	CB 9	CB 10	MOD 76	MOD 76B	MOD 78
As welded :					
Rp 0,2 (MPa)	760	810	729	743	769
Rm (MPa)	812	863	802	822	809
A%	22.4	19	20.3	18.8	20
Kv -40°C (J)- as	77	77	108	85	
Kv -40°C (J) - rh	115	120	114	133	
Kv -60°C (J)- as	60	62	75	50	77
Kv -60°C (J) - rh	83	95	86	108	125
After PWHT 580°C/3h :					
Rp 0,2 MPa	739	782	706	718	701*
Rm MPa	805	847	781	787	776*
A%	21.9	21.7	22.3	22.3	17*
Kv -40°C (J)- as	53	40	59	56	42
Kv -40°C (J) - rh	69	86	98	106	104
Kv -60°C (J)- as	27	-	43	34	23
Kv -60°C (J) - rh	37	47	81	88	66

* rupture on inclusion

1.1.2. P690 SAW WELDED JOINT

The fused weld metal chemical composition in a welded joint (Figure 2) is defined not only by the welding consumables but also by the plate material. In the example of formula MOD 78, the solidified metal in the root area consists of more than 50% of fused plate material. As such, the root pass chemical composition shows a contamination by Vanadium and Carbon coming from the plate and a severe loss of Nickel, Table 4. The top part of the weld has a composition closer to the pure weld metal; nevertheless the Vanadium content is almost twice as much as that of the all-weld-

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metal sample. The increase of the Carbon concentration increases the tensile strength. Also, the increase in Vanadium contributes to a loss in toughness, especially in the PWHT condition as Vanadium nitrides are formed during the tempering cycle. Finally, whereas the MOD 78 wire led to lower toughness in the all-weld-metal condition compared to MOD 76B, the trend is reversed when considering the real application in a welded joint, Table 4. With these results we consider that a better compromise is still likely to be found between toughness and tensile properties as an overmatching of about 100MPa was obtained. Formulation optimization was therefore pursued.

Table 4: Influence of base metal chemical composition on joint properties (weld preparation as in Figure 2). Note: notch position of the Charpy-V specimens always in the as solidified area.

		Mod 76B			Mod 78		
	Base metal	**Pure all weld metal**	**Joint**		**Pure all weld metal**	**Joint**	
			cap	**root**		**cap**	**root**
C	0.123	0.059	0.074	0.099	0.062	0,068	0,082
Si	0.3	0.36	0.35	0.33	0.31	0,35	0,32
Mn	0.81	1.58	1.35	1.14	1.4	1,43	1,12
Cr	0.63	0.47	0.51	0.56	0.25	0,36	0,45
Mo	0.43	0.36	0.38	0.4	0.44	0,48	0,47
Ni	0.9	2.5	2.26	1.68	2.62	2,43	1,87
V	0.053	0.008	0.017	0.031	0.004	0,015	0,028
O / N (ppm)	23 / 53	270 / 50	258 / 55	230 / 57	280 / 49	261 / 53	229 / 58
Strength As Welded	**Ts (MPa)**	822	822		809	835	
	Ys (MPa)	743	766		769	792	
	A%	18.8	15.5		20	17.5	
Toughness (J) As Welded	**-20°C**	-	-	60	-	90	54
	-40°C	85	92	45	-	-	-
	-60°C	50	45	36	77	92	59
	-80°C	-	-	-	55	59	44
Toughness after PWHT 580°C / 3h	**0°C**	-	-	35	-	-	-
	-20°C	88	-	25	-	90	54
	-40°C	56	56	-	42	60	40
	-60°C	34	27	-	23	34	25
Strength After PWHT 580°C / 3h	**Ts (MPa)**	787	837		776*	861	
	Ys (MPa)	718	754		701*	791	
	A%	22.3	18.3		17*	19.2	

* rupture on inclusion

1.2. DEVELOPMENT FOR SHIELDED METAL ARC WELDING OF 690MPA STEELS

A covered electrode for SMA welding of P690QL steel was also developed with the aim to provide satisfactory toughness after a PWHT of 580°C/3h. The first development step consisted in searching the optimal pure weld metal chemical composition to achieve acceptable Charpy-V values at –40°C after PWHT, while overmatching the yield strength of the base material. This was performed in the flat position according to the procedure defined in AWS A5.5 standards. In addition, while optimizing weld metal chemical composition in order to favor high toughness after PWHT, special attention was taken to develop products with as minimum impurities responsible for temper embrittlement as possible, therefore featuring as low a Bruscato index as possible. This latter is expressed as: $\mathrm{X-bar\ (Bruscato\,index\ for\ weld\,metals)} = \frac{10 \cdot \mathrm{P} + 5 \cdot \mathrm{Sb} + 4 \cdot \mathrm{Sn} + \mathrm{As}}{100}$, with compositions of Phosphorus, Antimony, Tin and Arsenic given in ppm, these elements known to segregate at grain boundaries to cause temper embrittlement. With a X-bar of 15 as a maximum permissible value, this could be achieved through a careful control of the purity of raw materials and steel rods employed for the production of covered electrodes. As such, as temper embrittlement

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not only depends on tempering time and temperature and weld metal chemical composition, but also on the cooling rate from the tempering cycle, our development method also consisted in computing the shift between Charpy-V values measured after PWHT 580°C/3h + 50°C/h cooling and those after PWHT 580°C/3h + quench, as a function of the Bruscato factor value of experimental welds. Thus, data points of Figure 4 describe the relationship between these two figures, clearly demonstrating the necessity to use high-quality raw materials for welding applications for which a PWHT is to be carried out. Thus, the composition of final electrodes developed for 690MPa steel welding applications featured a Bruscato index of about 7.

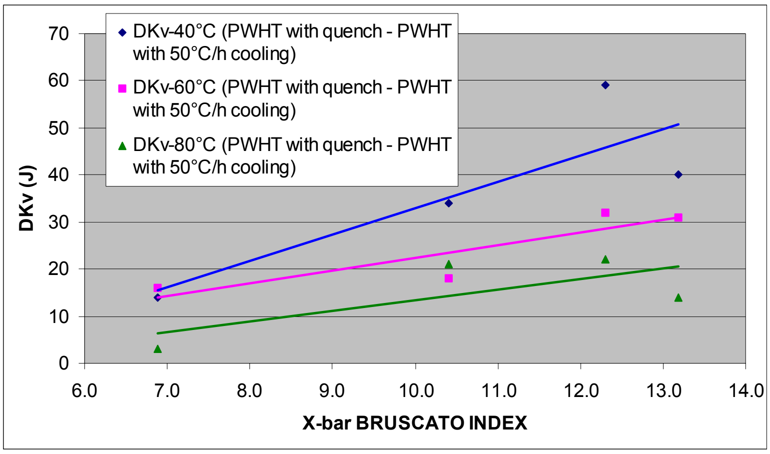
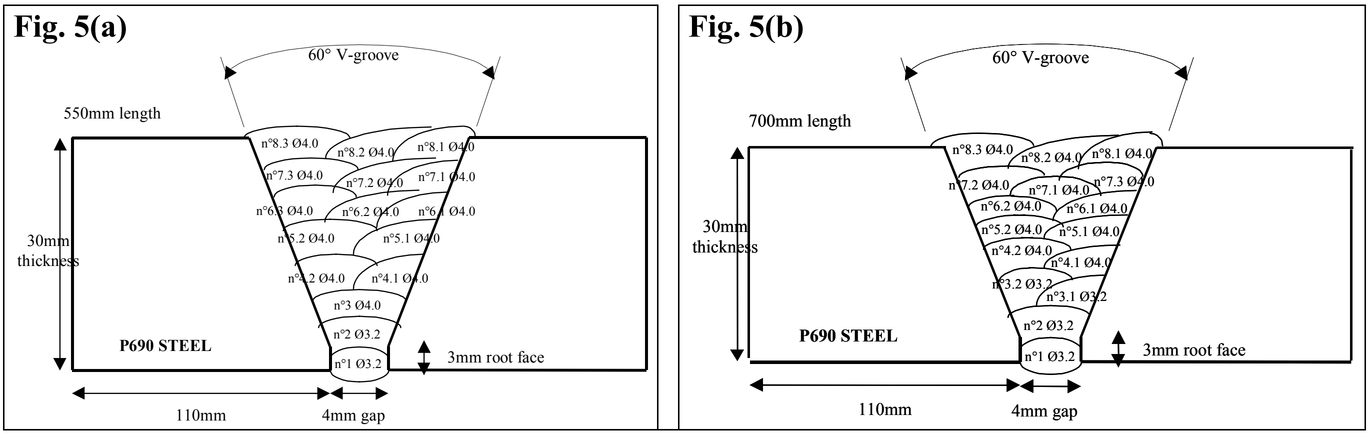


Figure 4: Variation of DKv; the shift between toughness after PWHT 580°C/3h + 50°C/h cooling and toughness after PWHT 580°C/3h + quench, as a function of the Bruscato factor of welds.

In a second step, welded joints were prepared on P690QL plates using the developed electrodes in the PF position. As such, a first joint was prepared using the L-037 Ø3.2mm and the L-036 Ø4mm electrodes, according to the bead sequence described in Figure 5(a). Welding parameters were 90 / 120A for Ø3.2 / 4mm electrodes, 17-25kJ/cm welding energy, preheating temperature of 120°C, interpass temperature of 150°C and soaking at 150°C.



Figures 5(a)-(b): Layer build-up / electrode sequence of 1st and 2nd joints using 690MPa electrodes.

As seen in Table 5, the chemical compositions of pure weld metal samples and the corresponding first joint are significantly different. Again, dilution of the base metal into the weld pool partly explains such differences. The increase of Vanadium in the root pass accounts for the contamination originating from the base metal. When comparing the chemical analysis of the root zone with that of the cap zone, one can see that the contamination in the cap is lower.

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Table 5: Influence of base metal chemical composition on weldments properties, from all-weld-metal samples to welded joints using of SMAW Ø4mm L-036 and L-039 formulae.

		L-037 Ø3.2mm	L-036 Ø4mm			L-039 Ø4mm			
	Base metal	Pure all weld metal	Pure all weld metal	First joint		Pure all weld metal	Second joint		
				cap	root		cap	½ th.	root
C	0.123	0.056	0.056	0.080	0.077	0.064	0.074	0.070	0.067
Si	0.29	0.37	0.38	0.41	0.30	0.38	0.42	0.40	0.34
Mn	0.81	1.43	1.30	1.35	1.27	1.31	1.36	1.30	1.32
Cr	0.64	0.27	0.26	0.28	0.30	0.27	0.27	0.28	0.33
Mo	0.42	0.39	0.42	0.43	0.41	0.43	0.41	0.40	0.39
Ni	0.96	2.34	2.56	2.71	2.17	2.67	2.63	2.50	2.08
V	0.051	0.010	0.010	0.011	0.015	0.010	0.013	0.010	0.015
O (ppm)		380	390	310	390	360	330	330	390
N (ppm)	49	77	78	88	130	69	110	113	140
Strength As Welded	**Ts (MPa)**	811	788	814		784	801		
	Ys (MPa)	779	732	749		719	732		
	A %	17.4	18.4	16.2		20.0	18.6		
Toughness (J) As Welded	**-20°C**	-	-	-	68	-	88	-	77
	-40°C	114	96	61	47	98	66	98	54
	-60°C	91	53	44	37	76	34	-	37
	-80°C	73	-	29	-	69	-	-	-
Toughness after PWHT 580°C / 3h	**-20°C**	-	-	54	45	76	53	-	50
	-40°C	64	50	38	22	53	45	47	41
	-60°C	56	35	-	-	34	28	-	24
	-80°C	46	-	-	-	-	-	-	-
Strength After PWHT 580°C / 3h	**Ts (MPa)**	803	795	820		796	808		
	Ys (MPa)	456	733	716		733	711		
	A%	19.1	21.1	19.2		18.0	22.3		

The Carbon content measured over the joint is also unexpectedly high compared to the all-weld-metal sample, remaining almost unchanged from the root to the cap region. All-weld-metal pads prepared at various currents revealed that the electrode formulation was partly responsible for this, as C%, Si% and Mn% were dependent on current, Table 6. As the PF/3G1 position of the joint demanded a lower current than for the PA/1G position of the pure weld metal (120A vs. 160A), formulation changes were brought to L-036 formula to reduce its sensitivity to current variations.

Table 6: Variation of the composition of the ∅ 4.0mm experimental L-036 electrode with current.

	C%	**Si%**	**Mn%**	**Cr%**	**Mo%**	**Ni%**
120A	0,073	0,42	1,35	0,27	0,44	2,61
140A	0,056	0,38	1,27	0,26	0,43	2,57
160A	0,055	0,37	1,22	0,26	0,47	2,63

The PF position is also the reason for higher Nitrogen concentrations in the joint. The reverse side of the penetration pass in the root region is only hardly protected by gases generated by the electrode coating fusion. The Nitrogen level, therefore, becomes higher due to a dilution effect from the penetration pass up to the cap region. Also, contact with the ambient air unavoidably induces Nitrogen pick-up throughout the joint preparation as a chimney effect takes the protective atmosphere away from the metal. As a consequence, Nitrogen pollution in the weld metal decreases the toughness in the as-welded condition and induces the precipitation of Niobium and Vanadium carbo-nitrides during PWHT (part of these elements being introduced from the plate material), which are detrimental to toughness. In contrast, in the flat position (PA, PB) the Nitrogen pick-up

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would be lower and hence the toughness higher. The PF position chosen here thus appears as a worst-case scenario.
As the first joint did not show good enough results, a second joint was prepared with:

- modified ingredients to make the ∅4.0mm electrode less sensitive to welding current variations (e.g. the Carbon level transferred to the weld metal less dependent on current);
- a modified welding sequence to create more re-heated weld metal which exhibits better toughness than the as solidified one.

As seen in Table 5, the composition of the second joint exhibits Carbon concentrations of 0,067-0,074% compared to 0,075-0,080% for the first one, demonstrating the improvement of the L-039 formula compared to the L-036 through flux ingredients adjustments in the electrodes coating. Mechanical properties are also given in Table 5: an improvement could be obtained in the second joint, particularly in the root region. Interestingly also, the value obtained in the mid-thickness region is significantly higher than those measured both in the root and the cap regions, particularly in the as-welded condition. The presence of higher proportion of reheated structure in the mid-thickness region, as shown in Figure 5, is undoubtedly of prime importance to explain such an increase in toughness.
As such, it was possible to improve the existing formulation for covered stick electrodes for P690QL steel so that a PWHT could be carried out. It is therefore possible to achieve Charpy-V > 47J down to -40°C in a joint, providing that the layer built-up guarantees a maximum of re-heated weld metal and that care should be taken to maintain as short an arc as possible in order to minimize Nitrogen pick-up, in particular when welding in the out-of-position is to be performed.
Optimization is currently still on-going on covered electrodes formulation to reach Kv -60°C > 47J in the as-welded condition and Kv –40°C > 47J after PWHT. The latest formula presented in Table 7 was developed on basis of L-039 formula with a reduction in weld metal oxygen content, an increase in Mn% and a tight control of the weld metal impurity level. Characterization on a joint is still pending with this product.

Table 7: All-weld-metal properties of latest SMAW Ø4mm electrode for E690 steel for PWHT.

		L-078 Ø4mm: pure all weld metal		
C%		0.062		
Si%		0.40		
Mn%		1.42		
Cr%		0.26		
Mo%		0.40		
Ni%		2.56		
V%		0.009		
O / N (ppm)		340 / 90		
Strength As Welded	Ts (MPa)	786	828	Strength After PWHT 580°C / 3h
	Ys (MPa)	719	767	
	A %	20.0	18.0	
Toughness (J) As Welded	-40°C	91	74	Toughness after PWHT 580°C / 3h
	-60°C	80	52	
	-80°C	56	42	

2. WELDING SOLUTIONS FOR 830MPA STEELS

It is the aim of designers to improve the performance in the manufacture of jack-ups for self-lifting platforms used for offshore oil exploration, i.e. to reduce the structures thickness, weight and corresponding costs [Ref. 5]. Correspondingly, in order to replace structures typically fabricated using 690MPa steel grades (e.g. A517), Industeel recently developed a new steel, Superelso 830, with a yield strength over 830MPa, for as-welded applications. Interestingly, this new quenched-tempered, hot rolled steel features a level of toughness of 50 J at -60°C throughout the whole

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thickness of the plate (89 and 160mm thicknesses). Jack-ups consist of a toothed racks with reinforcements in the shape of half-shells welded on each side of the toothed rack faces. Welding thus appears as a critical operation in the manufacture of these sections and an Industeel / Air Liquide Welding collaboration led to the characterization of a sub-arc flux-wire combination and covered electrodes specifically developed and adapted to the new 830MPa steel grade. The weldability of the material was then characterized in order to make sure the implementation and welding of this new product was feasible in comparison with the traditional procedure using the former steel of lower strength.

A first multi-pass joint was prepared on base plates of dimensions 1000 x 350 x 160mm using the tubular Ø3.2mm Fluxocord 83 / OP 121 TT/W wire / flux combination in 1G / PA welding position. Welding parameters were as follows: 55cm/min travel speed, 30V, 550A DC+, heat input of 18.1kJ/cm, preheat temperature of 120°C, interpass temperature of 170°C and 250°C/2h soaking treatment. Table 8 summarizes mechanical properties obtained in the joint in comparison with those of the pure weld metal: a yield strength well above 830MPa was guaranteed in the weld metal, as well as an ultimate tensile strength above 870MPa and an average toughness level above 59J at -60°C (Mini > 47J).

Tables 8(a-b): Mechanical properties of the pure weld metal vs. joint for SAW on E830 steel.
Note: for toughness “as” corresponds to the as solidified area, “rh” to the reheated area.

T.8(a)	**Base metal**	**Pure all weld metal**
C	0.141	0.063
Si	0.18	0.42
Mn	1.30	1.49
P	0.007	0.011
S	0.001	0.004
Cr	0.31	0.25
Mo	0.57	0.49
Ni	4.26	2.84
V	0.031	0.004
Nb	0.001	0.001
O/ N (ppm)	-	300 / 81

T.8(b)		**Pure all weld metal**	**Joint**	
Strength As welded	**Ts (MPa)**	903	956	
	Ys (MPa)	867	901	
	A %	17.5	18.0	
			Cap	**Root**
Toughness (J) As welded	**-40°C as**	84	-	-
	-40°C rh	104	-	-
	-60°C as	67	61	85
	-60°C rh	89		
	-80°C rh	48	-	-
	-80°C as	66	-	-

A second joint of dimensions 1500 x 350 x 160mm was welded for DNV qualification on base plate using the Ø3.2 and 4mm Tenacito 83 covered electrodes in PC/2G welding position, Figure 6. Welding parameters were as follows: 10-20cm/min travel speed, 110-150A DC+, heat input of 15.9kJ/cm, preheat temperature of 120°C, interpass temperature of 150°C and 250°C/2h soaking treatment. Toughness values measured from weld metal to base plate on both sides and center of joint are described in Figure 7. Mechanical properties obtained in the joint are reported in Table 9, in comparison with those of the pure weld metal. These are in agreement with the targeted values (Ys>830MPa; Ts>870MPa; Kv-60°C>50J).

Weldability tests performed in multi-pass joints demonstrated the conformity of SAW and SMAW products to overmatch the 830MPa strength level of this new steel, while guarantying a toughness level above 50J at -60°C. Note that the analyses of the SAW and SMAW consumables were not selected the same as a higher content of Nickel of the coated electrodes could favor higher Charpy-V values without any risks for hot cracking, in contrast with the SAW combination.

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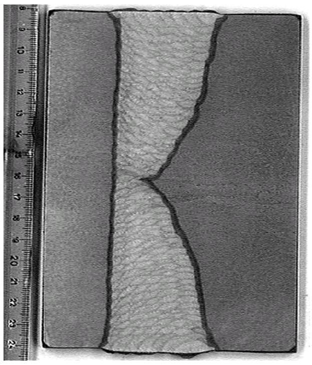

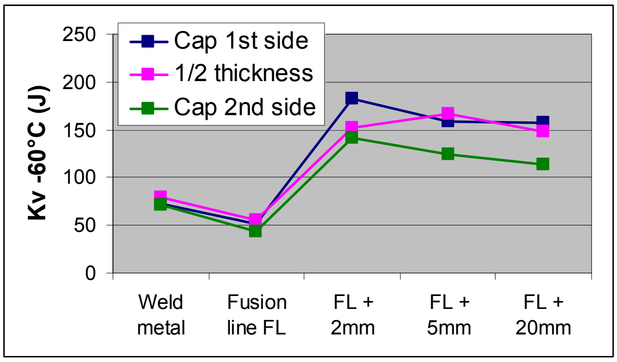

Figure 6: Macrography of the joint welded with Tenacito 83 electrodes in Superelso 830 steel (10° K-joint, 160mm thickness).

Figure 7: Toughness profile from weld metal to base plate in joint prepared in Superelso 830 steel.

Tables 9(a-b): Mechanical properties of pure weld metal vs. joint for SMAW on E830 steel.

T.9(a)	Base metal	Pure all weld metal *	Joint
C	0.141	0.047	0.048
Si	0.18	0.36	0.34
Mn	1.30	1.36	1.32
P	0.007	0.007	0.010
S	0.001	0.007	0.007
Cr	0.31	0.039	0.029
Mo	0.57	0.54	0.52
Ni	4.26	4.83	4.94
V	0.031	0.013	0.010
Nb	0.001	<0.001	0.002
O / N (ppm)	-	330 / 65	398 / 75

* Ø4mm electrode

T.9(b)		Pure all weld metal *	Joint			
As welded properties :			Cap 1st side	½ th. 1st side	¼ th. 2nd side	Cap 2nd side
Strength	Ts (MPa)	888	885	889	924	892
	Ys (MPa)	856	854	849	888	859
	A %	17.0	14.8	18.2	14.2	17.6
	Ts (MPa)		Transverse: 863 to 861			
Toughness (J)	-50°C	96	-		-	
	-60°C	87	73	80	-	71
Hardness HV5kgf	weld metal		326	314	-	310
	base metal		285	277	-	280
	HAZ		409	372	-	391

Finally, trials were later carried out to investigate the possibility to develop another Ø2.4mm SAW wire (Chemetron technology with sheath) to be used with OP 121TT/W flux to satisfy PWHT criteria, i.e. Re > 830MPa and Kv –40°C > 47J. All weld metal characterization is described in Table 10. No joint has been performed as yet.

Table 10: Mechanical properties of pure weld metal for SAW wire on E830 steel for PWHT.
Note: for toughness "as" corresponds to the as solidified area, "rh" to the reheated area.

		FC75: pure all weld metal		
C%		0.075		
Si%		0.35		
Mn%		1.55		
Cr%		0.26		
Mo%		0.5		
Ni%		2.95		
O / N (ppm)		300 / 37		
Strength As Welded	Ts (MPa)	887	906	Strength After PWHT 580°C / 3h
	Ys (MPa)	855	871	
	A%	17.1	19.0	
Toughness (J) As Welded	-20°C as/re	-	86 / 107	Toughness after PWHT 580°C / 3h
	-40°C as/re	112 / 97	83 / 113	
	-60°C as/re	85 / 100	77 / 74	

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3. OVERMATCHING

Construction standards / codes often require that overmatching be obtained in the weldment compared with the base metal. Theoretically speaking, this means that the yield strength of the weld metal should be higher than the yield strength of the base metal. One reason for this demand is to avoid brittle fracture in the area around an eventual defect inside the weld metal. Even if there is no defect, in case of a stress event, a lower yield strength in the parent steel limits the maximum transferable stress to the weld metal and reduces the risk of grows of micro-voids which could then transform to defects. Practically speaking, prior to performing a structural weld, the filler metal is selected in a manner such that its minimum specified strength, $YS_{wm\ min}$ (i.e. that given in classifications), is higher than the acutal strength of the base metal to be welded, YS_{bm}. Actually, mechanical properties of a given steel can however significantly vary within a broad window, depending on the steel manufacturer, composition, processing route and thickness. Figure 8 shows common variations in mechanical properties for 355, 420, 450 and 690MPa steel grades. For instance it is highly possible that for a 420MPa steel, the actual yield strength reach 500MPa, i.e. +20% compared to the specified design strength. In such a case, the filler metal has to guarantee a minimum of 500MPa in the welded zone, in order for the overmatching condition to be satisfied, together with good toughness at -60°C, which is another necessary condition for structure integrity to be fulfilled.

Weld metal toughness and strength are two antagonistic properties and the achievement of one can generally be obtained at the expense of the other one, Figure 9. It is generally not a problem to guarantee a real overmatching for steels up to 500MPa together with good toughness at -60°C. For P690 steel, however, when the steel manufacturer does not guarantee the actual steel strength within the range $YS_{bm\ min}$ + 10%, the filler metal producer actually has to consider using a product with $YS_{wm\ min}$. > $YS_{bm\ min}$ + 10% + overmatching. As such, when the 690MPa steel features a real yield strength of 897MPa (i.e. $YS_{bm\ min}$ + 30%, Figure 8), the weld metal yield strength should be superior to 900MPa at least. Thus, it can become very difficult to guarantee both overmatching and toughness at -60°C and close control over the welding procedure has to be followed. This becomes more tricky, even impossible sometimes, when a 15% overmatching is prescribed by users for example or when a PWHT has to be performed.

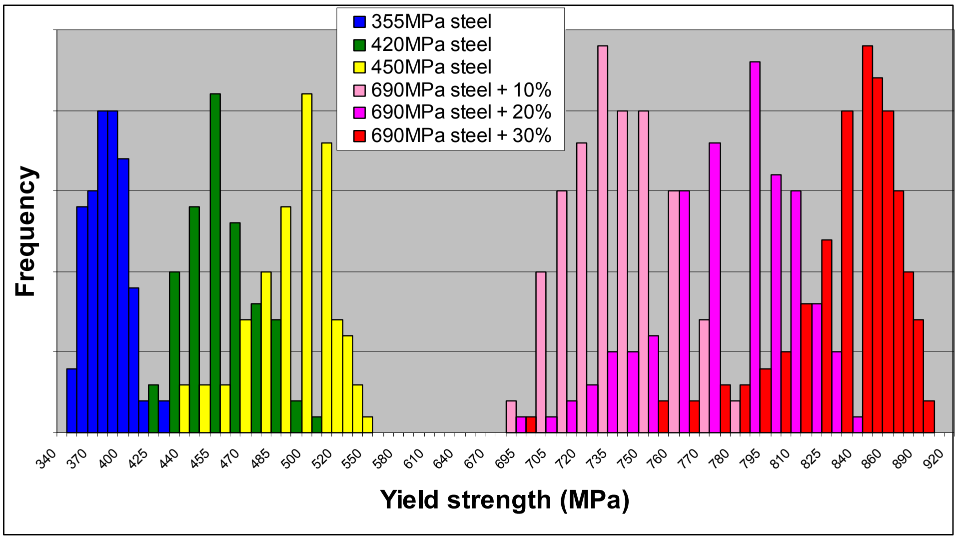

Figure 8: Illustration of yield strength distribution in 355 through 690MPa steel grades production.

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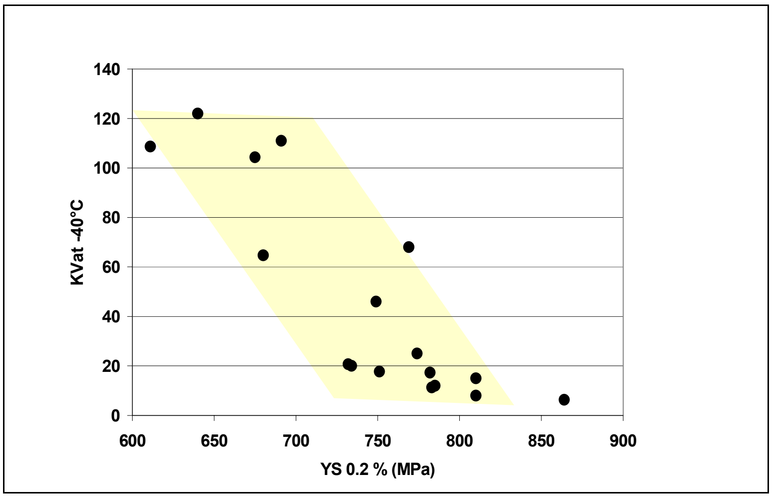

Figure 9: Relationship between weld metal toughness and yield strength (690MPa grade) [Ref. 4].

4. RESULTS ON STEELS IN THE 690-1100MPA RANGE

Table 11 gives an overview of results obtained on steels with yield strengths of 690MPa up to 1100MPa in the as-welded condition, using SMAW, FCAW and SAW consumables from Air Liquide Welding. From data in Table 11, one can see that up to around 850-900MPa, the current technology enables the weld metal to satisfy all technical specifications, i.e. overmatching and good toughness properties down to –40°C or even –60°C. As previously discussed, however, when welding of steels above 900MPa is to be carried out, good toughness values can only be guaranteed at the expense of tensile strength, and undermatching is often a solution. Conversely, if overmatching is needed, toughness at –40°C can not always fulfill the requirements.

Table 11: Mechanical characterization of welded joints prepared on steels with yield strength higher than 690MPa [Refs. 6-7].

	S690 25mm - V-groove - FCAW			S690 40mm - X-groove - FCAW				S890 29mm - V-groove - SAW		S960 60mm - X-groove - SAW				S1100 12mm - V-groove - SMAW		S1100 40mm - X-groove - FCAW			
	Base metal	Weld metal		Base metal	Weld metal			Base metal	Weld metal *	Base metal	Weld metal			Base metal	Weld metal	Base metal	Weld metal		
C%	0.18	0.08		0.17	0.09			-	0.09	0.16	0.09			0.18	0.1	0.16	0.08		
Si%	0.23	0.31		0.31	0.25			-	0.2	0.25	0.2			0.23	0.35	0.21	0.36		
Mn%	1.01	1.51		1.3	1.26			-	1.5	0.9	1.52			0.83	1.22	0.27	1.84		
P%	0.01	0.004		0.016	0.009			-	<0.020	0.009	0.018			0.005	0.006	0.003	0.008		
S%	0.002	0.005		0.002	0.005			-	<0.010	<0.00	0.006			0.001	0.006	<0.00	0.005		
Cr%	0.33	0.49		0.32	0.44			-	0.85	0.62	0.85			0.59	0.6	1.42	1.09		
Mo%	0.46	0.46		0.36	0.4			-	0.4	0.5	0.43			0.59	0.86	0.43	0.71		
Ni%	0.04	2.36		0.1	2.02			-	1.8	1.92	1.83			1.9	2.9	2.61	2.69		
V%	<0.001	<0.001		< 0.001	< 0.001			-	0.015	0.08	0.015			0.029	0.012	<0.00	0.005		
Ti%	0.003	0.005		0.002	0.003			-	0.001	0.002	0.001			0.003	0.006	0.001	0.009		
Nb%	0.03	0.002		0.025	0.003			-	<0.001	0.001	0.0008			0.018	0.004	0.001	0.003		
interpass T		150°C			150°C				250°C		180°C				180°C		150°C		
		cap	root		1.cap	root	2.cap		cap		1.cap	root	2.cap		cap		1.cap	root	2.cap
YS (MPa)	790	736	-	764	748	-	692	890 *	909	927	724	-	-	1221	914	1064	931	-	927
TS (MPa)	847	933	-	824	855	-	823	940 *	988	1001	859	-	-	1424	1062	1283	1061	-	1064
A%	15	17	-	17.5	19.5	-	18.5	16 *	19.1	15.5	19	-	-	12	19.5	11.5	14	-	13.5
TS (MPa) transverse		858			841				1023		885	922	873		1062		1004	-	1011
Fracture location		base metal: overmatching			base metal: overmatching				base metal: overmatching		weld metal: undermatching				weld metal: undermatching		HAZ: undermatching		
Kv-20°C (J)	75	74	74	130	73	73	95		83	?	119	139	117	52	66	55	46	84	42
Kv-40°C (J)	70	69	67	110	77	68	87		64	?	?	?	?	50	58	24	43	64	37
Kv-60°C (J)	60	60	53	73	58	-	61		-	?	?	?	?	44	54	-	33	-	35
TT 27J (°C)		-100	-90		-110	-70	-90				?	?	?		-100		-60	-70	-60

* typical values

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5. CONCLUSIONS

- The concept to produce higher strength steels with lean and economical chemical compositions by means of Vanadium instead of Nickel may cause welding difficulties. This is particularly true in the root region of welded joints, where toughness may not pass the requirements because of base plate dilution into the welded zone. Thus, the selection of a welding consumable from its all-weld-metal characterization can only be a starting point but is not a necessary condition to guarantee optimal toughness in a real welded joint. Instead, consumables featuring a high tolerance for contaminating elements coming from plate materials should be selected. As strength of structural parts increases, chemical analyses of steels and filler metals therefore have to differ. Such a flux-cored wire to be used in combination with OP 121TT/W flux makes it possible to obtain good toughness and strength even in the root region of P690 welds, both in the as-welded and PWH-treated conditions. Whenever possible, in order to optimize toughness, welding energy should be minimized and the layer built-up should be such that a maximum of re-heated weld metal be produced. In addition, in the case of SMAW, special care should be taken to maintain as short an arc as possible to minimize weld metal pollution by Nitrogen.
- As of now, the current technology enables the weld metal to satisfy both overmatching and good toughness properties down to -40°C up to around 850-900MPa structures. For example, an Industeel / Air Liquide collaborative work enabled the implementation of jack-ups for off-shore platforms in 830MPa steel grade instead of 690MPa through the development of SMAW and SAW welding consumables adapted to the new steel.
- Steels are defined for specified minimum strengths; filler metals are also defined for specified minimum strengths which can differ from those applying for steels. Also, ranges of chemical compositions and mechanical properties of steels can be somewhat wide for a given class of specified minimum strength. In addition, end-users have to cope with welding consumables with weld metal properties in specified ranges also. All these reasons make it difficult for filler metal designers to develop overmatching consumables while fulfilling toughness requirements in all conditions. As the application of welding consumables becomes less when restrictions in joint geometry, welding position, operability, heat input and PWHT apply, it is one goal of filler metal designers to improve stability in mechanical properties. In addition, as there is a will to increasingly use very high strength steels for structural applications, it is highly beneficial that steel manufacturers, weld metal designers and end-users collaborate closely.

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