High Strength Flux Cored Wire Taken To the Next Level

Improved impact properties of OUTERSHIELD 690-H

AWS A5.29: E111T1-K3M-JH4 ISO 18276-A: T 69 4 Z P M 2 H5

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Introduction

The application of high strength steels in offshore construction has become widespread. Grades equivalent to EN10025 S690Q are frequently applied to achieve a reduction in material thicknesses of up to 50% compared to traditional S355 steel grades. There is an ever increasing pressure on fabricators to lower production cost and cut production time. As a result, high productivity welding processes such as Flux Cored Arc Welding (FCAW) are increasingly applied in high strength steel construction. All-position flux cored wires with rutile slag systems are the preferred type of consumable as they combine high productivity and low post weld clean-up time.

OUTERSHIELD 690-H is a high strength FCAW wire with a rutile based slag system. The product was recently redesigned to meet the increasingly stringent mechanical property requirements in the offshore industry. The improvements have led to a product that takes high strength flux cored wires to the next level.

High Strength Steel

High strength steels with a minimum specified yield strength of 690 MPa have a well balanced chemical composition. They obtain their final microstructure and thus mechanical properties through accelerated cooling (Quenching) from the austenizing temperature, followed by a softening heat treatment (Tempering). The combination of relatively low carbon plus additional alloy elements (table 1), and the above described heat treatments lead to a soft and fine grained martensitic structure. This microstructure provides a high yield and tensile strength in combination with excellent ductility.

Table 1: Chemical composition (max. %) according to EN 10025 part 6

C	Mn	Si	Cr	Ni	Mo	Cu
0.2	1.7	0.8	1.5	2.0	0.7	0.5
Ti	B	N	Nb	V	Zr	
0.05	0.005	0.015	0.06	0.12	0.15	

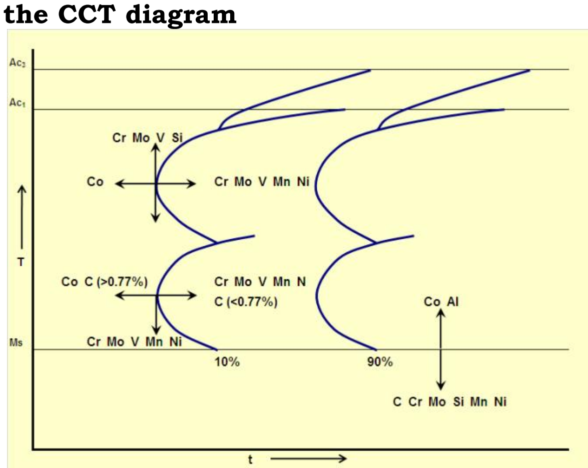
The chemical composition of these high strength Quenched & Tempered (QT) steels varies with the material thickness. The total alloy content increases with increasing material thicknesses and this increased alloy content results in a change in the critical cooling temperature during quenching. As a result, there is more time for the martensite transformation to take place in the core of the plate. This ensures that the required mechanical properties can be obtained though quenching and tempering. The increasing alloy content with increasing thickness for S690 steel is shown as a function of the Carbon Equivalent in table 2. The effects of alloy elements on the CCT diagrams are shown in figure 1

Table 2: Indicative Carbon Equivalents for S690 Steel[1]

Thickness (mm)	10	40	100	180
CEV (IIW)	0.40	0.51	0.63	0.71
PCM	0.24	0.29	0.32	0.34
CET	0.29	0.34	0.38	0.41

Carbon Equivalents
CEV = C+Mn/6+(Cr+Mo+V)/5+(Cu+Ni)/15
PCM=C+Si/30+(Mn+Cu+Cr)/20+Mo/15+Ni/60+V/10+5xB
CET=C+(Mn+Mo)/10+(Cr+Cu)/20+Ni/40

Figure 1 Influence of alloy elements on the CCT diagram



Although S690 type steels are considered to have good weldability, caution must be taken prior to welding to assure good mechanical properties in the Heat Affected Zone (HAZ). Specifically, both the preheat temperature and heat input need to be controlled. More details on preheat and heat input are provided in the Welding Execution section of this article.

Weld Metal Requirements

Both the AWS A5.29/5.29M & ISO 18276-A/B standards provide a basic framework for the standardization and classification of low alloyed flux cored wires. These standards provide, amongst others, requirements for chemical composition and mechanical properties of undiluted weld-metal

Additional requirements for both undiluted weld metal as well as diluted weld metal (welded joints) are set by approval agencies such as Lloyd's Register (LR), Det Norske Veritas (DNV), American Bureau of Shipping (ABS) and others. Finally, industry standards such as NORSOK also set forth requirements for welded joints. The requirements from the above mentioned standards and agencies, which are applicable to high strength flux cored wires, are shown in Appendix 1.

The minimum Charpy V-notch toughness requirements set by most of the "naval" based agencies, when certifying welding consumables to their rules, are substantially higher than the minimums set by AWS and ISO. OUTERSHIELD 690-H is classified as AWS A5.29: E111T1-K3M-JH4 and ISO 18276-A: T 69 4 Z P M 2 H5. These conformances require 27J average at -29°C for AWS, and 47J average with 32J as a minimum single value at the certified temperature for ISO.
Agencies such as LR, DNV GL require, in the case of high-strength fine-grained structural steel, that the weld metal with grade Y69 meets 69J average (10% of the minimum specified yield strength) at the certified temperature.

The requirements to obtain an agency approval on high strength welding consumables are often more stringent compared to the base material requirements and standard welding procedure qualification requirements. This to provide a safety factor. When following the DNV standards OS-C401 and OS-B101 the impact test requirements to qualify welding

[1] Dillinger Hütte GTS Technical information No III/2007

procedures are identical to the base metal requirements: 46J at the specified test temperature.

The minimum impact requirements set by DNV for "extra high strength steel" increase with the base material strength level (see table 3). Although it might seem initially counter intuitive, the increased toughness requirement does offset the decreased elongation requirement. This balances the total ductility of the weld.

Table 3; Mechanical properties for welded joints per DNV OS-B101 Table D2

DNV grade	Yield [MPa]	Tensile [MPa]	Elongation [%]	CVN [J]
NV X420	420	530-680	18	28
NV X460	460	570-720	17	31
NV X500	500	610-770	16	33
NV X550	550	670-830	16	37
NV X620	620	720-890	15	41
NV X690	690	770-940	14	46
X = A(0°C) D (-20°C) E(-40°C) F(-60°C)				

Weld Metal Chemistry

Several challenges need to be conquered before one can balance high strength and high impact toughness requirements with the use of a rutile slag system. A basic slag system could be used, as it facilitates the ability to meet the mechanical requirements. However, basic slag systems also result in poor welding characteristics (more spatter, difficult slag detachability) and lower productivity in all-positions.

From a chemical composition point of view, there are a variety of possibilities to reach yield strengths >690 MPa and impact toughness >69J @ -40°C. But the influence of essential elements in weld metal will always be heavily dependent on their weight % and or ratio with other elements. Prime examples are Manganese, Nickel, Titanium and Boron.

Manganese will improve the strength levels without a significant decrease of the elongation, but will affect the impact toughness once reaching yields above 560 MPa.

Nickel has a very strong positive effect on the impact properties, but can both increase and decrease the strength of weld metal depending on its weight %. The Mn/Ni ratio also plays key role in the optimization of the impact toughness properties.

Boron and Titanium are so-called micro alloying elements, measured in part per million (ppm)[2] rather than parts per hundred (%). These elements act as nucleation points for grains upon solidification of the weld metal. Controlling both ratio and absolute content of both elements is paramount.

As important as having tight control over the chemical composition of the flux, is having full control over cored wire manufacturing variables such as %fill and the homogeneous distribution of alloy elements in the flux. This allows delivering wire with a high degree of consistency in mechanical properties, required to meet stringent customer requirements.

[2] 1ppm = 0,0001%

Weld Metal Properties

By redesigning OUTERSHIELD 690-H, the weld metal is now able to comfortably meet the 69J @-40°C requirements. The scatter of the individual impact toughness values is low, providing sufficient comfort in properly executed welding procedures. Impact values that were obtained from the welded joints are given in table 4. The impact values before the re-design were typically around 60-70J @-40°C.

Table 4: CLW CVN Impact properties from 20mm welded joints in S690T

Temp	Position	V1[J]	V2[J]	V3[J]	Avg[J]
-40°C	PA/1G	90	95	87	91
	PC/2G	92	94	88	91
	PE /4G	81	95	87	87
	PF/3G↑	76	87	80	80
	All weld	83	85	92	87

Cross weld tensile specimens were taken from the welded plates as well as bend test samples. The results are reported in table 5. The cross weld tensile specimens failed in the weld which is not uncommon because of the substantially higher tensile strength of the base material. All obtained values exceeded the minimum requirements.

Due to different acceptance criteria, bend testing was performed according to 5d/120° and 4d/180°. No indications were found.

Table 5: Cross weld tensile test and bend test results

Position	Rm [MPa]	Fracture Location	Bend 5d/120	Bend 4d/180
PA/1G	795	Weld	Acc	Acc
PC/2G	816	Weld	Acc	Acc
PE/4G	796	Weld	Acc	Acc
PF/3G↑	792	Weld	Acc	Acc

Welding Execution

Obtaining good mechanical weld metal properties in high strength steel requires tight procedure controls.

Heat Input (HI)[3] and layer thickness are crucial parameters to control during welding. Weld bead thicknesses varying between 2,0mm and 2,5mm have proven to provide excellent impact toughness in all welding positions while still practical to execute by the welder. Limited weaving is required to achieve these weld bead thicknesses. The HI associated with these weld bead thicknesses generally range between 1.1 and 1.4 kJ/mm.

The weld metal strength is under normal conditions, amongst others, controlled by its chemistry. Excessive dilution during welding can lead to a reduction in the weld metal strength. This is due to the differences in chemistry between base and all-weld metal chemistry. Proper penetration in the base material obviously needs to be assured but excessive focus of the arc on the base material needs to be avoided, in order to minimize dilution.

Pre-heating the base material prior to welding could be necessary due to the chemical analysis as well as the combined thickness. EN 1011-2 provides a guideline for pre-heating. The Lincoln Electric Europe Pre-Heat Calculator, which is based on the above mentioned EN standard, is recommended to determine the required pre-heat temperature. Most steel mills also provide a good set of guidelines for preheating.

[3] HI [kJ/mm] = (UxI)/vx1000)

The interpass temperature should be restricted in order to preserve the deposited weld metal structure. A practical interpass temperature could be 150°C (max 200°C)

Approvals

The upgrade of OUTERSHIELD 690-H and the consistent impact properties well above 69J at -40°C allowed for all relevant agency approvals for offshore and alike applications. Table 6 provides an overview of the available approvals and grades.

Table 6: Available approvals and Grade

Approval Agency	Grade
American bureau of Shipping	4YQ 690 H5
Det Norske Veritas	4/IV Y69S H5
Lloyds Register	4Y69S H5
Germanischer Lloyd	4Y69 H5 S
Registro Italiano Navale	4Y69 S H5

Conclusion

The upgrade of Outershield 690-H has led to an all position flux cored wire delivering consistent mechanical properties with impact toughness well above 69J at -40°C, meeting the 4Y69 (or equivalent) approval grade.

Outershield 690-H has a rutile slag system that offers excellent weldability and slag detachability. This, combined with a stable and well directed arc, reduces post weld clean-up to a minimum.

The wire offers substantial productivity improvements over conventional stick electrodes with classification E11018M.

Effective and practical welding procedures have been developed to balance productivity and mechanical properties.

Appendix 1:

Classification & 3rd party requirements

Element (weight%)	AWS A5.29	ISO18276-A	Specification
C	0.15	0.03-0.10	0.040-0.080
Mn	0.75-2.25	-	1.30-1.70
Si	0.80	0.90	0.10-0.40
P	0.03	0.020	0.020
S	0.03	0.020	0.020
Cr	0.15	0.2	0.15
Ni	1.25-2.60	-	1.8-2.1
Mo	0.25-0.65	-	0.40-0.65
Nb	-	0.05	0.05
Cu	-	0.3	0.08
V	0.05	0.05	0.03

	AWS	ISO	ABS*	DNV*	GL*	NORSOK
ReL / Rp0,2 [MPa]	-/680	690 / -	-/690		-/690	690 / -
ReH				690		
Rm [MPa]	760-900	770–940	770-940	770-940	770	770–940
A4/A5 [%]	15/-	-/17	-/17	-/17	-/17	-/17
CVN @ -29°C	-/27					
CVN @ -40°C		32/47	-/69	-/69	48/69	
CVN @ -46°C						-/42

* Requirements for approval entry test