WELDING IN CRYOGENIC APPLICATIONS WITH STAINLESS AND NICKELBASED CONSUMABLES.

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Stainless austenitic materials and 9% nickle steels offer high ductility even at very low temperatures and are used for cryogenic applications. Consumables and procedures have been developed for welding of stainless and nickel alloyed cryogenic materials to give optimum strength/ductility in the welds and allow for safe operations.

Some of the essential factors influencing the ductility of austenitic weld metal at cryogenic temperatures is the level of ferrite in the weld metal and the amount of micro slags.

A number of vessels in 316 LN modified type of steel have been welded with a specially developed nitrogen alloyed weld metal allowing tensile strength > 615 MPa and KV-196>35 J.

Nickelbased weld metals have been designed for 9% nickel steels to achieve the combination of tensile strength >680 MPa and KV-196>70 J.

This paper will present weld metal investigations and practical welding of 9% nickel steel LNG storage tanks, welding of the transonic wind tunnel project and welding of 316 LN transportation tanks for LNG.

Key words : Ductility, cryogenic, nitrogen, ferrite, austenitic, 9% Ni.

INTRODUCTION

The word "cryogenic" stems from the greece word "cryos" which simply means freezing temperature. Although no clear definition exists it is probably considered that cryogenic temperatures signifies temperatures below -100°C. Cryogenic temperatures are required in gas processing down to -269°C to liquify gases, and in the storage and transportation of liquified gases.

For the construction of transportation vessels and storage tanks for LNG the material must posess very high ductility at these low temperatures to minimize risk for brittle fractures. Below -100°C carbon manganese steels or low alloyed 2-3.5% nickel steels can not longer be used due to their low toughness but austenitic stainless and 5-9 % nickel steels can meet the necessary requirements on ductility.

Austenitic stainless steels.

Austenitic chromium nickel stainless steels such as AISI 304 types are used for low temperature applications in construction of vessels and in pipes in cryogenic constructions. Austenitic steels do not show any pronounced transition temperature and they are ductile also at temperatures below -196°C. In order to increase the strength of austenitic chromium nickle steels and thereby reduce the thickness in the construction other alloying elements will be used. Nitrogen is a very potent and inexpensive solid solution strenghtener and may be added up to 0.35% and will also improve the corrosion resistance as will be discussed later. The nitrogen bearing AISI 304 LN contains about 0.15 N and the yield strength is about 80 MPa higher than for AISI 304L without reducing the ductility significantly.

Weldability of austenitic steels is excellent since no hardening transformations takes place and since they are not very sensitive for large variations in heat input or cooling rate. Weld metal should be of a similar composition as the parent metal i.e. type 308L weld metal for 304 L or 304LN steels.

The composition of the weld metal is designed to give a small amount of retained delta ferrite in the weld metal.

Table 1 :
Liquefaction temperatures of gases and used types of parent materials

Gas	Liquefaction Temperature(°C)	Type of parent material used
Ammonia	-33,4	Carbon steel
Propane	-42,1	Fine grain Al-killed steel
Propylene	-47,7	2,25 % Ni steel
Carbon Dioxide	-78,5	
Ethane	-88,4	
Ethylene(LEG)	-103,8	5-9 % Ni Steel
Methane (LNG)	-163	
Oxygen	-182,9	
Nitrogen	-195,8	Austenitic stainless steel
Helium	-268,9	Al alloys

Table 2

Ferrite content and impact strength at - 196oC for the SMAW weld metals

SMAW weld metal No.	1	2	3	4	5	6	7	8	9	10
Ferrite content (FN)	1,1	1,9	2,9	3,2	3,4	4,0	4,2	5,4	5,5	6,6
Impact strength (J)	44	42	44	40	44	39	35	36	29	30

This ferrite, normally in the order of FN 5-10 is considered essential to reduce the tendency to solidification or liquation cracking.

On the other hand for cryogenic purposes increased content of ferrite reduces the notch toughness so the ferrite content should be at the lowest possible level (1).

Under very critical conditions it has been found necessary to tailor make the consumables based on the actual analysis of the used raw materials to be able to keep the composition and the ferrite content in the desired narrow range.

The level of micro slag in the weld metal and its content of oxygen has very high influence of reducing the ductility of the weld metal. For all slag forming welding processes as SMAW, SA, FCW, the slag therefore should have a high basicity to achieve ductility at cryogenic temperatures. An oxygen content below 400 - 500 ppm should be aimed for and can only be obtained with basic slag.

The European Transonic Wind Tunnel ETW

ETW is a windtunnel being constructed in Cologne Germany with unique performance design to simulate flight conditions. This is being done by reducing the tunnel operating temperature to 175°C thereby increasing the Reynolds number by a factor of 6. The ETW aerodynamic circuit is about 150 mtr long comprising about 2200 tons of stainless steel in thickness mainly 11-60 mm and a diameter of the tunnel ranging from 4 up to 12.2 mtr. The plate was specified by DIN 17440 Werkstoff Nr 1.4301 (AISI 304LN) and supplied by British Steel.

The prefabrication of 35 sections were made in Babcock and Wilcox Renfrew works in Scotland and transported to Cologne for assembly by Lentjes A.G. Fig. 1 Gives a view from fabrication of sections.

Because of the heavy thickness submerged arc welding was intended to be used to a very great extent in the workshop. After the evaluation of the process productivity finally about 80% of the welding consumables used were FCW and MMA.

The requirements on the weld metal mechanical properties were :

R_m 500-700 MPa $R_{p0.2}$>195 MPa A_5>40 % KV-196°C >35 J.

To further verify the ductility a value of min 0.38 mm lateral expansion was also required at - 196°C.

A basic coated 308L type (OK 61.35) was developed with a ferrite content FN4-7.

During the early procedure qualification test it was, however, found that the heavy plate thickness and resulting heat dissipation influenced the ferrite morphology in a negative way. The ferrite tended to develop a continuous network which reduced the impact resistance.

Modifications of the weld metal composition and the resulting ferrite level could however reduce the sensitivity to differences in heat input and cooling rate.

LNG Transportation vessel tanks in 316 LN

Further to adding nitrogen, alloying of the austenitic chromium steel with molybdenum will improve the corrosion resistance even more in relation to : PRE = % Cr + 3.3 % Mo + 16% N(2).

Several liquified gas tankers have been built in Italy using 316 LN steel.

Table 3

OK 61.35 (308L-15)

	KV-196°C	R_p 0.2 MPa	R_m MPa	A_5 %
Requirements All weld metal	z35J	>195	500-700	z40
Original veriant, FN 4-7				
All weld metal, Pos. 1G	55 J High heat input	440	580	45
All weld metal, Pos. 1 G	35 J Low heat input	-	-	-
X joint 50 mm, Pos. 4 G	30-38 J	-	-	-
Modified variant, FN 2-3				
X joint 50 mm, Pos. 4 G	46-48 J	-	-	-

Typical all weld metal Analysis C 0.03 Si 0.4 Mn 1.7 Cr 18.8 Ni 10.3 Lateral Expansion 0.55

Table 4

Cargo Tanks in 316 LN Modified Grade

	C	Mn	Si	Cr	Ni	Mo	N	P	S
Typical analysis - Plate	0.020	1.45	0.040	18.4	11.5	3	0.15	0.030	0.010
OK 69.25 - All weld metal	0.030	6.5	0.40	19.5	16.5	2.8	0.15	<0.015	<0.010

R_m657 MPa KV-196oC 52 J $R_{p0.2}$ 463 MPa A_4=38.6 %

Table 5

Consumables for 9% Ni steel. Typical all weld metal composition (wt. %)

Consumables SMAW	C	Si	Mn	Cr	Ni	Mo	Nb	W	Fe
OK 69.46	0.2	1.0	8.0	18	14			4	bal.
OK 92.55	<0.060	0.7	3	13	bal.	6.5	1.3	1.5	4
SAW, Wire/flux									
OK Autrod 19.82/									
OK Flux 10.16	0.01	0.35	0.3	20	bal.	9	3.0		1.5

$$B = \frac{CaO + CaF_2 + MgO + K_2O + Na_2O + 1/2(MnO + FeO)}{SiO2 + 1/2(Al_2O_3 + TiO_2 + ZrO_2)}$$

The tanks are 2-3000 m^3 and of so called bilobated shape to fit the ship design.

The requirements on weld metal are R_m>615 MPa $R_{p0.2}$>290 MPa

KV - 106°C > 27 J HB max 220 M_o>2.7%.

A plain 316 L chromium nickel molybdenum weld metal cannot meet the requirements on mechanical properties specified for these tanks and it was necessary to develop a basic electrode with the weld metal containing of nitrogen among others. This austenitic weld metal with nitrogen and molybdenum will give both the tensile strength and impact resistance required.

This type of fully austenitic weld metal is also to be used for welding of 316 LN when weld metal with ferrite not can be accepted due to selective corrosion. This is for example the case in handling nitric-acid cargo.

With a fully austenitic weld metal there could however be risk for solidification cracking but a high manganese content together with low residuals and a basic coating has proved to give satisfactory performance.

9% Nickel Steels

9% nickel steels are used invariably for the construction of large landbased LNG storage tanks, i.e. 50-100.000 m3 volume. These steels provide a combination of strength and ductility at a reasonable cost. The excellent low temperature impact properties are the result of a fine grained structure of tough nickel-ferrite (3).

Because of its low carbon content 9% nickel steels are not susceptible to underbead cracking or to excessive hardening in the HAZ. The portion of austenite in the steel may absorb hydrogen. It can be welded at a thickness of at least 60 mm without preheating and no PWHT is required by ASME Pressure Vessel Code up to this thickness.

Matching compositions of 9-12% nickel weld metal have not been possible to develop to give a satisfactory result. Nickelbased weld metals or austenitic stainless weld metals containing tungsten are used.

The thermal expansion coeficient of nickel based weld metals closely matches the 9% nickel steel itself. The stainless weld metal has about 40% higher expansion which favors the yse of nickelbased weld metals in application involving thermal cycling.

The ductility of the weld metals is investigated in several ways. Impact resistance is generally required to be minimum 70 J at - 196°C. At the same time a lateral expansion of 0.38 mm use to be requested. CTOD tests also are performed and crack open displacement sare often specified to give less than 0.3 mm Crack Tip Opening Displacement at - 196°C.

Due to the magnetic properties of the 9% nickel steels arc blow makes it impossible to use MIG welding. Submerged arc welding can be used and SMAW electrodes are designed to operate well on AC which largely eliminates this problem.

When it comes to the assembly of large storage tanks, submerged arc welding is generally used for the circumferential welds and manual metal arc for the vertical welds.

In the submerged arc welding a solid wire of a similar composition is used together with an agglomerated flux of high basicity. Basicity for submerged arc welding fluxes is calculated according to the well known index by Tuliani, Bonisewski and Eaton :

is given above

When the index is 1.00 the flux is neutral, if it exceeds 1.00 it is basic and if less than 1.00 it is acid. In this case a flux with a very high basicity i.e. basicity index > 2.00 was used.

The use of small diameter wire 1.6 mm is recommended to facilitate the welding in 2 G position and to give high notch toughness in the weld metal.

Table 6 shows mechanical properties SMAW and for Submerged Arc Welding.

Lateral expansion of 1.5 mm and CTOD values of 0.45 - 0.5 mm are obtained at -196°C in the weld metals of OK 92.55 and OK Autrod 19.82/OK Flux 10.16.

SAW is operated on DC negative polarity on the electrode. This reduces the penetration and the dilution of parent metal and improves the resistance to solidification cracking. X or K joints are used to enable welding from both sides and to reduce the stresses that could result from welding.

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Table 6

Consumable classification and typical all weld metal mechanical properties.

Consumables	AWS classific	$R_{p0.2}$ (MPa)	R_m (MPa)	A_5 (%)	Charpy-V (J) -196°C	-120°C	-90°C
SMAW :							
OK 69.46	- *)	480	650	41	43	63	
OK 92.55	NiCrMo-6	450	710	40	85	-	
SAW, Wire/flux :							
OK Autrod 19.82/ OK Flux 10.16	ERNiCrMo-3**)	425	700	41	80	100	

*) Classified according to DIN 8556 **) Wire classification

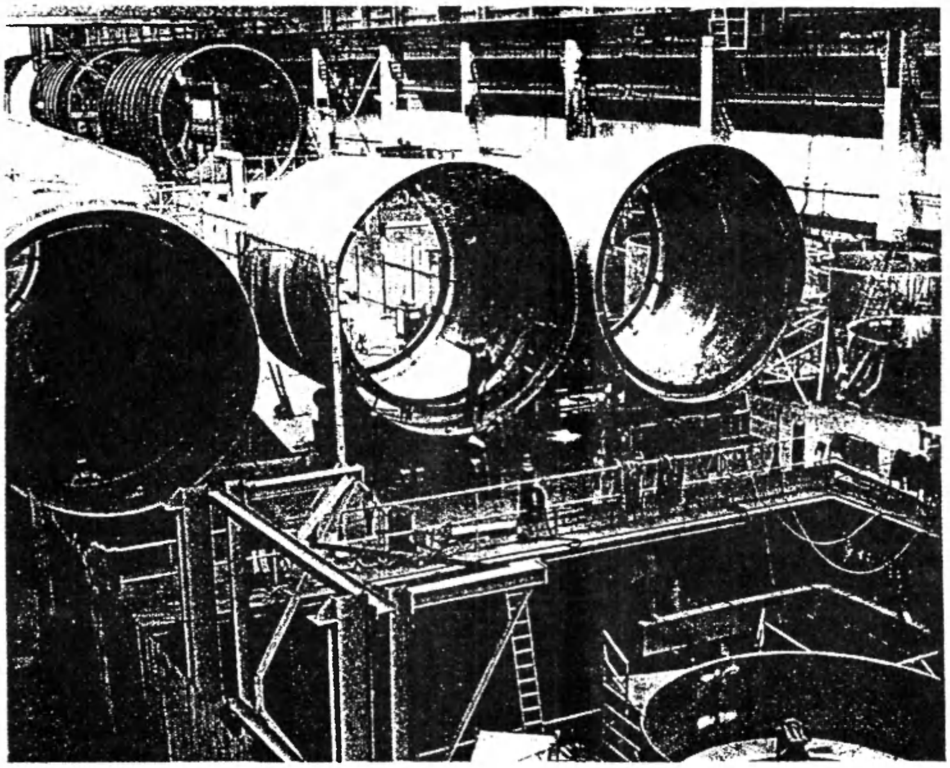

Fig 1: View from fabrication of sections fro ETW (Babcock and Wilcox Renfrew works Scotland)

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