Electrodes for Welding 9% Nickel Steel

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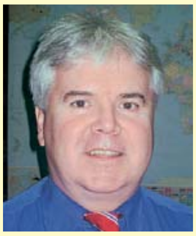
3 authors, including:

Jan Hilkes
Voestalpine

Fred Neessen

Welding 9% nickel steel for liquefied natural gas (LNG) applications



***Jan Hilkes**, BSc, CEng. FWeldI, IWE, is a Registered International Welding Engineer with a degree in metallurgy/metallurgical engineering. As Technical Manager he has presented various technical papers and conducted numerous welding seminars for Lincoln Smitweld and Lincoln Electric all over the world. Subjects included all materials, arc welding processes and related applications. He has over twenty years of experience in the welding industry. He is currently Commercial Manager at Lincoln Smitweld in the Netherlands.*

***Fred Neessen**, BSc, EWE, is a European Welding Engineer with a degree in mechanical engineering. As Technical Manager Consumables and Consultant at Lincoln Smitweld he is conducting technical training seminars on welding and applications in all industries around the world. He has presented many technical papers on welding at International Conferences and is much appreciated for his clear, practical and explanatory speeches on difficult subjects. He has close to 30 years of industrial experience including about 25 years in welding.*

For more than five decades, storage facilities for liquefied natural gas (LNG) are being built with 9% nickel steel in order to obtain sufficient ductility and structural integrity at –163°C and below. Although research has been carried out with matching welding consumables for the welding of these applications, at present still only nickel base consumables have proved to meet the requirements such as mechanical properties. This paper will briefly describe the history of 9% nickel steel [1]. A more detailed description will be given of the metallurgy of 9% nickel steel, the nickel base welding consumables and the welded joints in relation to the chemical composition, heat treatments, mechanical properties, physical properties, international specifications and project requirements for LNG tanks. For the welding of 9% nickel steel with SMAW and SAW, some practical guidelines will be presented and exemplified with recent reference projects. Lincoln Smitweld has been involved with the development of welding consumables for 9% nickel steel, as for example the Nyloid 2 covered electrode, for over 30 years.

Jan Hilkes and Fred Neessen, Nijmegen/The Netherlands

1 Introduction

For economical reasons there has been an increasing demand worldwide for the use of liquefied gases next to oil. First to be less dependent on unstable prices and risks of supplies of oil and second to exploit the gassy side product of oil exploration. A third reason is because gas is also a less polluting fuel with lower CO_2 and sulphur bearing emissions, which would contribute to a better control of global pollution. In addition to the existing natural gas wells this brings about a vast quantity of gas to be treated, handled, transported and stored around the world. By liquefying gas its volume is reduced by about 600 times, which makes it much easier and economical to handle and store in reasonably sized storage facilities on land or on ships. Liquefied natural gas (LNG) can be obtained by cooling methane gas down to a temperature of at least –163°C.

At these extremely low temperatures standard ferritic structural steels are not suitable anymore, mainly due to lack of sufficient toughness and the risk of brittle fracture. For this reason the ferritic steels are not supposed to be used in pressure vessels with service temperatures below –101°C. Cryogenic 9% nickel steels have been developed to achieve the mechanical properties required for building storage tanks and spheres that offer a reliable structural integrity down to –196°C. The pronounced transition temperature as present for ferritic steel fades away when up to about 9% nickel is added to the steel. This reduces the risk of brittle fracture tremendously. The development of 9% nickel steel started already over five decades ago at the International Nickel Company Laboratories and it became recognised by the ASME Code for cryogenic use in 1954. Since then 9% nickel steel has been widely used for LNG storage facilities around the world. However, the development continued as the requirements for the steel, the welding consumables and the structural integrity have been increased with the years.

Nowadays, LNG storage tanks are being constructed according to the "double integrity concept", which means that the tank consists of a cryogenic steel inner shell and a concrete outer shell. The shell insulation in the inter-space between the two shells consists of a heavy insulation such as perlite and a resilient fibreglass blanket. This type of construction assures that the liquid gas will be retained within the outer shell just in case anything happens with the cryogenic inner shell. An example of which is given in Figs. 1 and 2, from the Dabhol LNG Terminal Project in India for which Skanska Whessoe designed, constructed and commissioned three huge full containment storage tanks with 9% Ni steel

***Fig. 1.** Dabhol LNG terminal India, site overview of one of the three 9% Ni tanks that have been built by Skanska Whessoe according to the "double integrity concept" with a capacity of 163,000 m^3.*

Fig. 2. Dabhol LNG terminal India, inside view of the construction of the 9% Ni steel inner shell and the concrete outer shell for one of the three tanks built by Skanska Whessoe according to the "double integrity concept" with a capacity of 163,000 m³.

inner shell [13; 14]. These tanks have been built each with a capacity of 163,000 m³. This required a tank with an inside diameter of at least 75 m and a height of minimal 37 m. To provide sufficient strength the wall thickness in this case starts with 27.5 mm for the first course. More details of this project will be discussed with the applications further along in this paper.

Mechanical requirements and project specifications for the parent material, all weld metal and the welded joints may include: Yield strength, ultimate tensile strength, cross tensile strength, elongation, side bend test, impact toughness (CVN), lateral expansion, shear fraction and CTOD. The last four properties may have to be determined at –163°C and/or –196°C. The latter is a very practical testing temperature since liquid nitrogen can be used as a cooling medium.

In order to present the full picture, the base material, the welding consumables and the welding of 9% Ni steel will be described and discussed in detail.

2 Base material

As mentioned before one of the critical properties for low service temperature materials is notch toughness (ductility) and reduction of the risk on brittle fracture at the respective low service temperatures. In general the optimum mechanical properties of nickel alloyed materials can be achieved and improved by:

- having low levels of impurities as for phosphorus and sulphur,
- having careful control of interstitial alloying elements as carbon and nitrogen,
- applying treatment with aluminium to combine with interstitial atoms such as oxygen,
- using the optimal combination of other alloying elements as C, Mn and Mo to balance strength, toughness and cost effectiveness,
- applying a heat treatment that generates the optimum fine grained structure of tough nickel-ferrite with small amounts of stable austenite in 9% Ni steel.

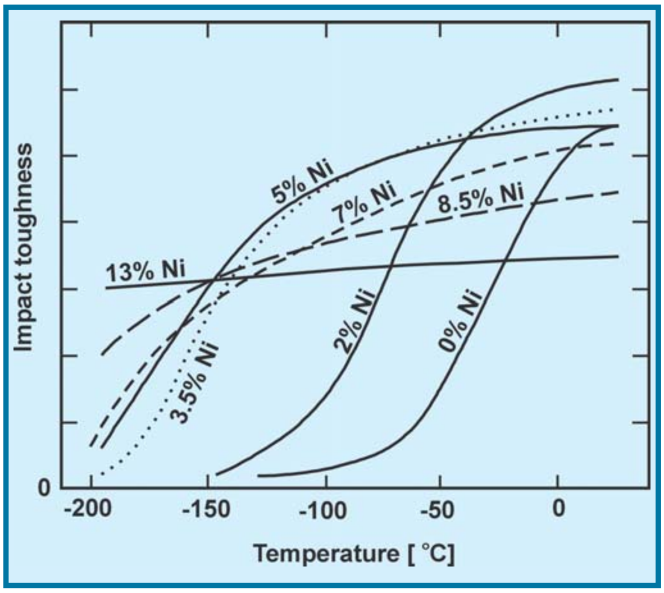


Fig. 3. The effect of nickel content on low temperature impact toughness and transition temperature of normalised low carbon steels. (Armstrong and Brophy)

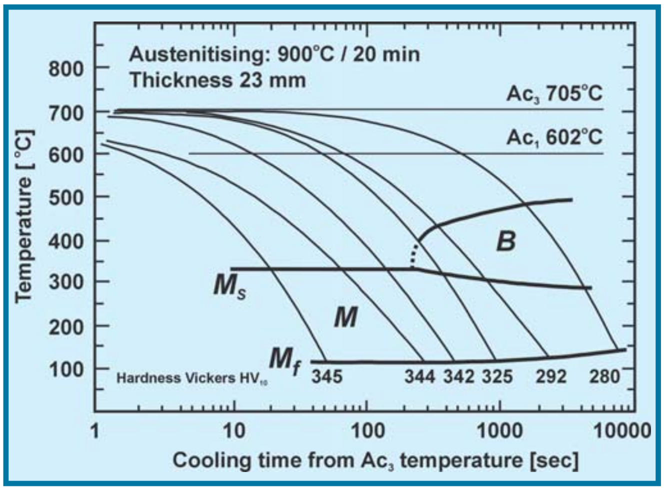


Fig. 4. Continuous cooling transformation (CCT) diagram for a 9% Ni steel with: 0.09% C, 0.22% Si, 0.68% Mn, 9.02% Ni, 0.008% P, 0.009% S and 0.03% Al (IIS/IIW-844-87).

Influence of nickel in steel

The main contribution of nickel in steel is the significant improvement of toughness and impact strength at cryogenic subzero temperatures [7]. Nickel is also very effective in improving the hardenability of steel because it reduces the critical cooling rate that is necessary to produce hardening on quenching. This makes it easy to carry out heat treatments. The combination of an increased nickel content with the proper heat treatment such as normalising or quenching and followed by tempering will significantly increase the impact toughness and substantially lower the transition temperature all the way down to –196°C. Fig. 3 shows the effect of various nickel contents on the low temperature impact toughness and transition temperature of normalised

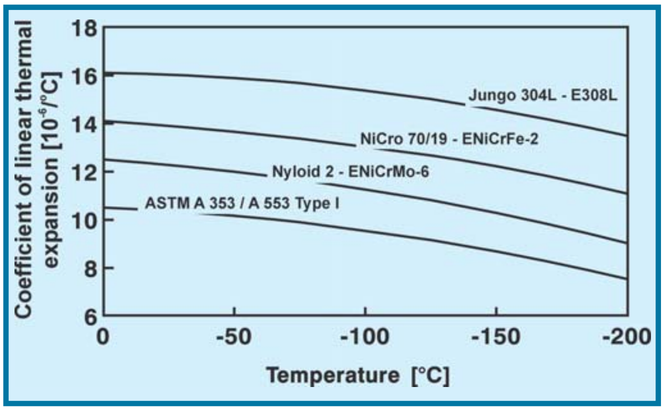


Fig. 5. *Comparison of the coefficient of linear thermal expansion of 9% Ni steel with that of welding consumables Jungo 316L, NiCro 70/15 and Nyloid 2.*

low carbon steels. In this figure, steels have been evaluated with nickel contents up to 13% at which level the ductile-brittle transition is not notable anymore at any temperature. However, the practical and cost effective optimum has been established around 9% nickel which is still the basis for the modern 9% Ni steels of today.

Metallurgy

For low carbon, high purity 9% Ni steels the ferrite-austenite transitions take place at an Ac_1 of 602°C, which is a much lower temperature than the conventional Ac_1 temperature of 723°C. In fact the Ac_1 for 9% Ni steel is actually replaced by a two-phase field of austenite and ferrite, in which equilibrium conditions are only slowly attained. Nickel contributes to this because it suppresses the formation of ferrite/perlite high-temperature transformation product. Hence, a microstructure is produced which is higher in strength and in impact toughness due to the presence of stable retained austenite and nickel-rich ferrite.

The addition of 9% Ni also lowers the M_s and M_f temperatures down to about 325 and 100°C respectively and no perlite will be observed. This is illustrated in Fig. 4 that shows the continuous cooling transformation diagram of a 9% Ni steel [1]. Due to the low M_f temperature unstable austenite will remain after cooling from austenitising temperature to room temperature. A tempering treatment in the $\alpha+\gamma$ region above the lower critical temperature allows nickel to stabilise the austenite. In the tempered martensitic matrix small quantities, 5 to 10 volume percent, of high carbon nickel-austenite are formed which remain stable at cryogenic temperatures as –196°C. In this case the austenite derives its high carbon content from the solution of carbides present as a grain boundary network. As a result, the reduction of an embrittling carbide network increases the low temperature toughness. At lower cooling rates, a mixture of austenite-ferrite and carbides in a martensitic matrix can be formed. This implies that for 9% Ni steel the microstructure of a heat affected zone (HAZ) in a welded joint will always be martensitic, even at very low (air-)cooling rates [8].

Obviously developments in the steel-making process such as electric arc furnaces with dephosphorisation and ladle refining with desulphurisation as well as vacuum degassing have made a great contribution to the quality and constant improvement of the properties of 9% Ni steels. The high purity and cleanliness assures excellent low temperature impact toughness and crack arrest properties but has also eliminated the risk of temper embrittlement. The latter has a very positive effect on the weldability of the 9% Ni steel.

Heat treatment

As described before, the heat treatments are the key to success, to arrive at the desired microstructure with the corresponding mechanical properties that are required.

Good strength and low temperature impact toughness are present with a microstructure containing nickel-rich ferrite and stable high carbon austenite. This can be produced by:

☐ double-normalising and tempering (NN+T),
☐ quenching and tempering (Q+T).

Double-normalising is carried out at about 900 and 800°C to produce a homogeneous structure. Water quenching or air cooling from about 800°C provides a structure with low carbon martensite and bainite, which rarely has hardness in excess of 400 HV.

Subsequent tempering at about 570°C, which is marginally above the lower critical Ac_1 temperature, produces a structure with high nickel-ferrite, carbides and reformed stable austenite in which carbides have been resolved. This structure has a high strength and a high impact toughness level. Due to the carbon content, the high carbon austenite remains stable to temperatures below –196°C and contributes to the toughness at cryogenic service temperature. For nickel levels of less that 7% there is no formation of stable austenite on tempering which differentiates 9% Ni steel from other low temperature martensitic steels. The main effect of the austenite is to remove embrittling carbides from the matrix. When all the carbides have been converted to stable austenite in this way, the steel offers maximum low temperature impact toughness.

Manufacturers of 9% Ni steel, e.g. Industrieel Arcelor Group [3], Creusot-Loire [4] and Bethlehem Lukens Plate [2], have reported similar data on the heat treatments applied for their cryogenic materials:

- ☐ NN+T: 900°C air cooled, 790°C air cooled and 570 to 610°C air cooled,
- ☐ Q+T: 800 to 820°C water quenched and 570 to 610°C air cooled.

In general, 9% Ni steel that is quenched and tempered will show higher yield strength and higher CVN impact toughness values at –196°C as opposed to the double-normalised and tempered material.

For this reason the Q+T steel is often used for the inner shell of tanks or for the hulls of a vessel. For structural or other parts that are subject to deformation the NN+T steel is regarded more suitable.

Base material specifications

In order to distinguish between the NN+T and the Q+T steel, ASTM refers to different specifications:

- ☐ ASTM A 353/353M-93 (1999): Standard Specification for Pressure Vessel Plates, Alloy Steel, 9% nickel, double-normalised and tempered. (NN+T)
- ☐ ASTM A 553/553M-95 (1999): Standard Specification for Pressure Vessel Plates, Alloy Steel, quenched and tempered, 8 and 9% nickel. (Q+T); (Type I = 9% Ni and Type II = 8% Ni).

The main difference is the minimum yield strength for the NN+T is 515 MPa and 585 MPa for the Q+T (Type I). A complete overview of the chemical and mechanical requirements according to the above ASTM standards is given in Table 1.

The 9% Ni steels are also specified in EN 10028-4 and JIS G 3 127, but in most cases the ASTM standard is referred to.

3 Welding 9% Ni steel for LNG applications

The welding of 9% Ni steel for LNG applications determines for a great deal the structural integrity of the total construction. It is therefore very important to evaluate the welding processes that can be applied as well as the possibilities in type and chemical composition of the consumables. The optimum combination should provide the best mechanical properties to assure the integrity in combination with a suitable economy. The requirement for 9% Ni steel LNG tanks these days are very strict and have been increased over the years to make optimum use of the strength of this material [5; 6]. Combining all the specifications for projects Lincoln has recently been involved in, would give the following mechanical requirements for the weld metal of the consumables to be used for welding 9% Ni steel:

- ☐ yield strength: > 430 MPa,
- ☐ ultimate tensile strength: 690 to 825 MPa,
- ☐ elongation: > 35%,
- ☐ impact toughness (CVN): > 70 J at –196°C,
- ☐ lateral expansion: > 0.38 mm at –196°C,
- ☐ shear fraction: > 80% at –196°C,
- ☐ CTOD: > 0.30 mm at –165°C/–196°C.

Welding processes for 9% Ni steel

The welding processes suitable for welding 9% Ni steel are most of the actual arc welding processes such as with stick electrodes (SMAW), with solid wire and gas (GTAW and GMAW) and with submerged arc welding wire and flux (SAW).

The gas welding processes are very suitable for shop-welding of piping and thin plate material but are usually not very appropriate for site welding under severe outdoor conditions that could jeopardise the gas-protection needed to assure the quality of the welded joint. Particularly GTAW is also very low in deposition rate, which makes it unfavourable for a reasonable economy.

Manual GMAW requires very skilled welders with an endless concentration ability to keep the proper pace required for sufficient welding progress in the vertical up position. In addition, this

Table 1. *Chemical and mechanical requirements according to ASTM A 353/353M-93 (1999) for double-normalised and tempered 9% Ni steel and according to ASTM A 553/553M-95 (1999) for quenched and tempered 9% Ni steel.*

Standard	ASTM A353 / A353M (NN + T)		ASTM A553 / A553M (Q + T)	
Chemical composition				
Element	Heat [%]	Product [%]	Heat [%]	Product [%]
Carbon	≤ 0.13		≤ 0.13	
Manganese	≤ 0.90	≤ 0.98	≤ 0.90	≤ 0.98
Phosphorus	≤ 0.035		≤ 0.035	
Sulfur	≤ 0.035		≤ 0.035	
Silicon	0.15 - 0.40	0.13 - 0.45	0.15 - 0.40	0.13 - 0.45
Nickel	8.50 - 9.50	8.40 - 9.60	8.50 - 9.50	8.40 - 9.60
Tensile requirements				
	[ksi]	[MPa]	[ksi]	[MPa]
Tensile strength	100 - 120	690 - 825	100 - 120	690 - 825
Yield strength, o.2% offset	≥ 75	≥ 515	≥ 85	≥ 585
Elongation in 2 in. (50 mm)	≥ 20.0%		≥ 20.0%	
Charpy impact energy absorbtion @ - 195°C				
	Average	Single	Average	Single
Longitudinal	≥ 34 Joule	≥ 27 Joule	≥ 34 Joule	≥ 27 Joule
Transverse	≥ 27 Joule	≥ 20 Joule	≥ 27 Joule	≥ 20 Joule
Remarks: Average of 3 specimens One single value	Each test specimen shall have a lateral expansion opposite the notch of not less than 0.381 mm (0.015 in.)			

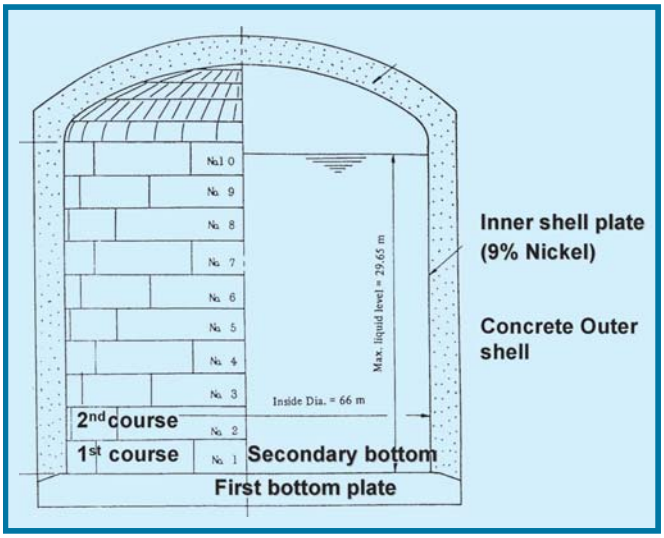


Fig. 6. *Schematic cross-section of a full containment LNG tank construction with 9% Ni steel inner shell and concrete/structural steel outer shell.*

process is relatively prone to welding failures such as lack of fusion, especially in heavy-thickness applications.

Welding with stick electrodes, however, is still a very flexible and viable process for welding under site conditions, all positions and all materials. A respected economy is also offered when using high recovery electrodes that are 450 mm long.

Whenever feasible submerged arc welding offers the highest productivity due to increased deposition rates, especially when mechanised as for example with girth welding systems. This process is suitable for almost all fillet and butt welds in the horizontal welding position. For site welding of 9% Ni steel storage tanks the most effective welding processes are SMAW and SAW.

Welding consumable considerations

Welding consumables for 9% Ni steel have been a subject of discussion as long as the base material is around, which means for over five decades. Consumables have been developed from "matching" ferritic types to high nickel alloys as 80 Ni/20 Cr/0.26 C [9]. Obviously, consumables with 80% nickel are extremely expensive and are more suitable for heat resistant applications. "Matching" ferritic consumables with up to about 12% nickel would offer an economic advantage in sheer cost of the product, but are still not accepted as a viable solution for storage tanks in sizes that are common in today's industry. Although a matching ferritic consumable has been successfully applied by mechanised GTAW to build a spherical model tank with 2 m diameter under laboratory conditions [10], this process is not widely used on site for welding storage tanks with 27.5 mm thickness and 75 m diameter.

Matching ferritic consumables with submerged arc welding has been used successfully in the production of 9% Ni steel pipe [11]. However, to obtain the required mechanical properties a post weld heat treatment had to be applied. This is feasible in a pipe factory but utterly difficult and impractical if not impossible on site or under most site conditions.

Some literature indicates that matching consumables with GMAW and GTAW in 20 mm plate only show 17 and 20% elongation respectively. One of the drawbacks of the matching consumable is the low elongation. Because it is similar to that of the base material, the residual stresses will be highest in the HAZ since on neither side of the HAZ the material can give in. For this reason consumables are needed that have a high elongation (>35%).

A further point of interest is thermal expansion, the LNG tank expansion and contraction while in service. LNG storage tanks, with all the welded joints, are subject to extreme thermal cycles. When the difference in coefficients of thermal linear expansion for the 9% Ni steel and the weld metal is too big, high thermal stress concentrations may give rise to thermal fatigue and failure of the tank. The coefficient of linear thermal expansion should therefore be as low as possible and that of the weld metal should be as close as possible to that of 9% Ni steel. Obviously matching consumable would score best but would not be an alternative for reasons as discussed before.

Fig. 5 shows the coefficient of linear thermal expansion for 9% Ni steel in comparison with various types of weld metal in function of the temperatures. The consumables included are an E308L type of stainless steel with 19 Cr/9 Ni, an ENiCrFe-2 type of nickel alloy with 70 Ni/19 Cr and an ENiCrMo-6 type of nickel alloy with 68 Ni/13 Cr/6 Mo. This graph shows that the ENiCrMo-6 type of consumable has a coefficient of linear thermal expansion that is closest to that of the 9% Ni base material. This is no coincidence because this type of consumable has been designed for welding 9% Ni steel.

Welding consumables for 9% Ni steel

As discussed before the sensible choice of consumable for welding 9% Ni steel is within the high nickel alloy range. Both for ductility/elongation and thermal expansion reasons nickel alloy consumables are the most appropriate. Obviously the cost of consumables is always being evaluated but all the properties, features and structural integrity that are present when using nickel alloy consumables, still offer the best overall solution. Within the scope of this paper the consumables for the SMAW and SAW processes will be discussed specifically and in more detail.

The welding consumable options with chemical composition and mechanical properties for SMAW covered electrodes are listed in Table 2 with the corresponding classification according to AWS A5.11. Depending on the specific project requirements a selection can be made [14; 15]. Although it seems that many options are at hand, only two electrode types meet the actual requirements as listed at the beginning of this chapter. The typical All-Weld-Metal (AWM) values listed show that the NiCro 60/20 (ENiCrMo-3) and Nyloid 2 (ENiCrMo-6) provide sound properties with sufficient cushion in view of the mentioned requirements. The Nyloid 2 is the most economical option of the two, both for cost of the product and for higher economy during welding because it is especially designed for welding 9% Ni steel. It also meets the CTOD, lateral expansion and shear fraction requirements at –196°C. This electrode has been around for over 30 years and has been constantly improved and

Table 2. *SMAW consumables for welding 9% Ni steel. (Covered electrodes: AWS A 5.11)*

Element	AWS A 5.11 (Covered electrodes)							
	E NiCrFe-2	**NiCro 70/15 E NiCrFe-2 * Typical AWM**	E NiCrFe-4 --	E NiCrFe-9 --	E NiCrMo-3	**NiCro 60/20 E NiCrMo-3 Typical AWM**	E NiCrMo-6	**Nyloid 2 E NiCrMo-6 Typical AWM**
C	0.10	**0.02**	0.20	0.15	0.10	**0.02**	0.10	**0.05**
Mn	1.0 - 3.5	**4.6 ***	1.0 - 3.5	1.0 - 4.5	1.0	**0.4**	2.0 - 4.0	**3.0**
Fe	12.0	**6.3**	12.0	12.0	7.0	**1.0**	10.0	**6.0**
Si	0.75	**0.43**	1.0	0.75	0.75	**0.3**	1.0	**0.4**
Cu	0.50	**0.03**	0.50	0.50	0.50	**0.02**	0.50	**0.02**
Ni	min. 62.0	**68,2**	min. 60.0	min. 55.0	min. 55.0	**62.0**	min. 55.0	**68.0**
Co	(e)	**N.D.**	--	--	(e)	**N.D.**	--	**N.D.**
Al	--	**0.04**	--	--	--	**0.03**	--	**0**
Ti	--	**0.1**	--	--	--	**0.1**	--	**0.03**
Cr	13.0 - 17.0	**17.3**	13.0 - 17.0	12.0 - 17.0	20.0 - 23.0	**22.5**	12.0 - 17.0	**13.0**
Nb (+Ta)	0.5 - 3.0	**1.9**	1.0 - 3.5	0.5 - 3.0	3.15 - 4.15	**3.5**	0.5 - 2.0	**1.5**
Mo	0.5 - 2.5	**0.9**	1.0 - 3.5	2.5 - 5.5	8.0 - 10.0	**9.0**	5.0 - 9.0	**6.0**
V	--	**N.D.**	--	-	--	**N.D.**	--	**N.D.**
W	--	**N.D.**	--	1.5	--	**N.D.**	1.0 - 2.0	**1.5**
Rm	> 550 (80 psi)	**665**	> 650 (95 psi)	> 650 (95 psi)	> 760 (110 psi)	**775**	> 620 (90 psi)	**720**
Rp0.2		**415**				**515**		**470**
Elong.	> 30	**44**	> 20	> 25	> 30	**44**	> 35	**39**
@ - 196°C		**124 J avg.**				**80 J avg.**		**85 J avg.**

Table 3. *SAW consumables for welding 9% Ni steel. (Solid wires: AWS A 5.14)*

Element	AWS A5.14 (Solid Wire)						
	ER NiMo-8 --	ER NiMo-9 --	ER NiCrMo-8 --	ER NiCrMo-3	**LNS NiCro 60/20 ER NiCrMo-3 Typical AWM**	ER NiCrMo-4	**LNS NiCroMo 60/16 ER NiCrMo-4 Typical AWM**
C	0.10	0.10	0.03	0.10	**0.01**	0.02	**0.02**
Mn	1.0	1.0	1.0	0.50	**0.1**	1.0	**0.6**
Fe	10.0	5.0	Rem.	5.0	**0.4**	4.0 - 7.0	**6.0**
Si	0.50	0.50	1.0	0.50	**0.4**	0.08	**0.4**
Cu	0.50	0.3 - 1.3	0.7 - 1.2	0.50	**0**	0.50	**0.01**
Ni	min. 60.0	min. 65.0	47.0 - 52.0	min. 58.0	**64.3**	Rem.	**balance**
Co	--	--	--	--	**N.D.**	2.5	**N.D.**
Al	--	1.0	--	0.40	**0.07**	--	**0.06**
Ti	--	--	0.70 - 1.50	0.40	**0.08**	--	**0.07**
Cr	0.5 - 3.5	--	23.0 - 26.0	20.0 - 23.0	**21.8**	14.5 - 16.5	**15.0**
Nb (+Ta)	--	--	--	3.15 - 4.15	**3.84**	--	**0.03**
Mo	18.0 - 21.0	19.5 - 22.0	5.0 - 7.0	8.0 - 10.0	**8.8**	15.0 - 17.0	**15.8**
V	--	--	--	--	**N.D.**	0.35	**N.D.**
W	2.0 - 4.0	2,0 - 4,0	--	--	**N.D.**	3.0 - 4.5	**3.5**
Rm	Not specified				**760**	Not specified	**720**
Rp0.2					**510**		**500**
Elong.					**46**		**35**
@ - 196°C	Remark: Typical AWM is Wire/Flux P 2000 combination				**80**		**80**

updated following the higher industrial standards and requirements for LNG storage tanks. In this context it should be noted that Nyloid 2 is also very suitable for economical welding of 3.5 and 5% Ni steel, as will be mentioned also in the chapter on applications. Specific features and benefits of the Nyloid 2 electrode are:

- ☐ basic coated stick electrode for all welding positions,
- ☐ 150% recovery,
- ☐ weldable on AC as well as DC,
- ☐ electrode length is 350 mm, except for 5.0 mm with a length of 450 mm,
- ☐ standard vacuum packaging in Sahara ReadyPack (SRP).

The basic coating provides optimal resistance against hot cracking due to the purifying effect on the weld metal. All position capability applies to all sizes except 5 mm diameter, which is most suitable for down-hand welding. A recovery of 150% implies that in addition to the 100% weld metal derived from the core wire an extra 50% of weld metal is produced from the electrode covering. This in addition with 450 mm electrode length gives a high productivity and high economy.

The electrode is designed with a nickel core wire to have a low electrical resistance in order to prevent overheating and subsequent deterioration of the covering. Weldability on AC is required since 9% Ni steel is notorious for having some magnetism that could give arc blow with possible subsequent weld-defects. Another advantage is the Sahara ReadyPack which is a vacuum packaging containing a convenient amount of electrodes for the welder and which assures the required quality and condition of the electrodes used on site. As far as production is concerned, the electrodes can be manufactured according to any lot classification, e.g. C3 or C5, as defined in AWS A-5.01-92. It also makes sense to obtain corresponding test certificates with actual values for the respective lot of electrodes.

The welding consumable options with chemical composition and mechanical properties for SAW wires and wire/flux combinations are listed in Table 3 with the corresponding classification according to AWS A5.14. As for the electrodes there are various options for welding consumable selection. Apparently the ER NiMo-8, ER NiMo-9 en ER NiCrMo-8 types of submerged arc welding wire are more used in Asia than in Europe and the USA. More common for this part of the world are ERNiCrMo-3 (LNS NiCro 60/20) and ERNiCrMo-4 (LNS NiCroMo 60/16) wires. Together with the appropriate submerged arc welding flux the wire/flux combination will provide very satisfactory results, meeting the requirements as listed at the beginning of this chapter. Available fluxes are P7000, P2000, P240 and LW380. P7000 is designated "SA AB 2 69 AC H5" according to EN 760-96, has a basicity of 2.5 and is especially designed for high nickel alloy wires to assure minimal risk of hot cracking. Due to the high basicity the slag-detachability may not meet expectations. P2000 is designated "A AF 2 63 DC" according to E 760-92, has a basicity of 1.7 and a nicer weldability, including slag release and is designed for stainless steel and nickel alloys. P240 is actually designed for structural steels in offshore applications but with a basicity of 2.9 it will provide crack-free weld metal. In the past P240 with LNS NiCroMo 60/16 has been tested with satisfying results. LW 380 is a fused flux with the advantage of not being hygroscopical, so ideal for site conditions. This flux is used in practice with a LNS NiCroMo 60/16 type of wire. Typical application for this wire/flux combination is welding in 2G position, on both sides simultaneously. Since further information is proprietary no more details can be given.

As shown in Table 3 the wire/flux combinations that meet the requirements as set out in this paper are LNS NiCro 60/20-P2000 and LNS NiCroMo 60/16-P2000. The All Weld Metal (AWM) properties for both variations do not differ much. The main difference is in the sensitivity to hot cracking and in cost/kg. LNS NiCro 60/20 is lower in cost/kg, for the same diameter, but due to its relatively high Nb-content there is an increased possibility of hot cracking. This can be caused for example by formation of Fe_3Nb, when the welding parameters are not carefully controlled. LNS NiCroMo 60/16 is higher in cost/kg but due to the much lower Nb-content it is less prone to hot cracking. However, the total welding cost has to be evaluated in order to make an intelligent welding consumable selection.

In addition to the listed mechanical properties, LNS NiCro 60/20-P2000 also fulfils the previously mentioned requirements regarding CTOD, lateral expansion and shear fraction at –196°C. This has been tested as part of welding procedure development for a recent 9% Ni steel project.

Welding 9% Ni steel LNG tanks with SMAW and SAW

After having discussed the 9% Ni steel base material and the welding consumables it is time to actually start to weld [14; 15]. Fig. 6 shows a schematic cross-section of a full containment tank as mentioned before in order to explain the various welding operations on site. It is clearly shown that the 9% Ni steel inner vessel is constructed out of large plates. The sizes depend on the suppliers rolling and heat treatment capacity and will therefore vary per supplier. For our example the sizes are 2.36 m × 3.38 m as used for the Dabhol project. The plate thickness ranges from 27.5 to 10 mm for the 1st to the 11th course. The shell stiffeners are 6 to 14 mm, the first bottom is 16.7 mm and the secondary bottom is 5 mm. All horizontal and vertical welds are butt-welded, stiffeners to shell are fillet welded and the secondary bottom is constructed with lap welds due to one side accessibility.

Welding joint preparations could be carried out by the supplier of the plates, in order to prevent additional handling and treatment on site. Joint preparations on site can be carried out by means of machining, plasma cutting or flame cutting. For the last two, the weld edges need to be cleaned by grinding to remove the overheated layer. When machining is used with a lot of deformation of the edges it is possible to end up with magnetism in the plate. Machining should therefore be carried out carefully in order

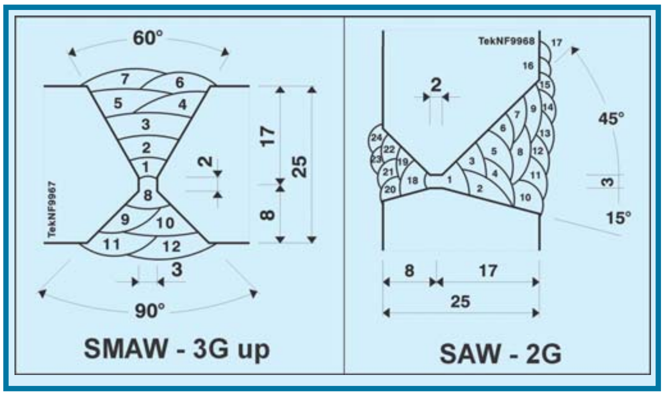


Fig. 7. *Weld preparation in 9% Ni steel for welding with stick electrodes (SMAW) in 3G vertical up position and for submerged arc welding (SAW) in the 2G horizontal-vertical position.*

Fig. 8. *Overview of the construction site of the Dhabol LNG Storage and re-gasification facility on the West Coast of India. (Courtesy of Skanska Whessoe U.K.).*

to prevent this. It is also suggested to clean also the adjacent base material on either side of the joint. Subsequent cleaning with for example acetone is required to prevent any contamination of the weld that could cause defects.

The 16.7 mm annular plates (first bottom) are welded in the flat position with SMAW for flexibility and it can be carried out with more welders at the same time for increased productivity. AC is used to prevent any possible arc blow that may be caused by magnetism in the 9% Ni steel base material. A maximum interpass temperature of 150°C should be respected and a heat input up to about 3 kJ/mm is acceptable. High-speed root runs are made with Nyloid 2 in 3.2 mm diameter on ceramic backing. The 5 mm diameter and 450 mm long electrode will contribute to productivity for filling and capping. SAW can be used in addition after sufficient weld metal is present to support the SAW without risking burn through. The groove preparation is a standard V-70° (V-groove with 70° included angle). The lap welds for the 5 mm bottom-plate were made with the high recovery Nyloid 2 since the edges are too thin for SAW (also with a tractor).

The first heavy horizontal weld is the first course of the shell to the annular plate, 27.5 to 16.7 mm. Weld preparation is a K-45° with little spacing. Due to limited accessibility the electrodes have been used here as well. With a diameter of 75 m the welding length of the circumference is 235.5 m to go around the tank once.

All vertical welds can be produced with stick electrodes out of position. Roots are usually made with a 2.5 mm electrode and subsequent filling and capping with 3.2 and 4 mm. Fig. 7 shows a typical joint preparation with weld-bead sequence for stick electrode welding in 3G-up position. For the subsequent courses where the thickness is reduced to 10 mm for the last four courses, similar preparation has been used with change from X to V for the last four courses.

During the procedure development all optimal currents have been established and documented in Welding Procedure Records, Specifications and Qualifications (WPR, WPS and WPQ). The welder qualifications have been carried out in accordance with the respective WPQ's. It has to be noted that the welders have to be properly trained and be made aware of the ins and outs of welding 9% Ni steel with a high nickel alloy consumable prior to welding qualifications.

All horizontal welding between the courses can be carried out with SAW after a root has been put in with stick electrodes. For this purpose a girth welding system is used to travel with the equipment along the courses during welding. As discussed it is possible to use the wire LNS NiCro 60/20 or LNS NiCroMo 60/16 both with flux P2000. The diameter is very important since it influences the deposition rate at a given current, hence, also the bead shape and the position of the bead in the joint. Optimum results have been obtained with LNS NiCro 60/20 in 1.6 mm and welding parameters as 220 to 250 A, 30 V and 500 to 620 mm/min. Depending on the position of the bead in the joint, the parameters are adjusted within this range. Fig. 7 shows the weld-joint preparation and bead sequence for submerged arc welding in the 2G position. The first course is 27.5 mm and the last four are 10 mm, which can all be welded with SAW. The last courses in 10 mm will only have a single-V preparation. An open root will allow a nice root run made with stick electrodes. If for whatever reason the root is closed, full penetration will not be achieved and back grinding with subsequent welding will be necessary. To obtain an optimum deposition rate DCEN polarity is recommended. In general, the deposition rate is primarily governed by the current density in the wire. Obviously the electrical resistance and I^2R effect in the wire plays a role but the main contribution is current density. Table 4 shows deposition rates for 1.6 and 2.4 mm nickel alloy wire with P2000 for various currents and polarities in the flat position. This shows clearly that a 1.6 mm wire can be welded with up to 300 A to give a deposition rate of 150 g/min. To obtain the same deposition rate with a 2.4 mm wire, the current has to be at least 350 A. This will be in the area where the bead is unacceptable regarding bead appearance and risk of hot cracking. It would be even more difficult to control the welding, i.e. welding pool and slag, when this was to be carried out in the 2G position. This implies that in order to have a 10 to 20% higher deposition rate with a 2.4 mm as with a 1.6 mm wire, the current has to be close to 400 A. This will not produce the desired bead-shapes and welded joint, hence, there is no need for using wires over 1.6 mm. Even when an ENiCrMo-4 type of wire in 2.4 mm diameter was to be used with less risk of hot cracking, there would be no advantage towards the welding economy.

Guidelines for welding 9% Ni steel

Although general information regarding the welding of 9% Ni steel has been given in the previous chapters a short summary is listed below [12]:

- ☐ Make sure that magnetism in the 9% Ni steel is not present or as low as possible.
- ☐ Obtain plate material with the proper joint preparation from the factory.
- ☐ Joint preparation on site can be carried out by machining, plasma cutting and flame cutting.
- ☐ If thermal cutting processes are used, all oxides and overheated material should by removed by grinding.
- ☐ The complete weld preparation (cleaning) should be carried out with acetone or other organic solvent.
- ☐ Preheating is not required in general when ambient temperatures are above 15°C.
- ☐ Welding processes SMAW and SAW can be used effectively.
- ☐ Nyloid 2 electrodes give high productivity due to 150% recovery.
- ☐ Use AC for stick electrode welding to prevent arc blow.

Table 4. *Deposition rate for submerged arc welding with LNS NiCro 60/20-P2000 in function of welding current, wire diameter and polarity.*

Bead on plate with 40 cm/min welding speed and a electrical stickout of 20 mm						
Current	Wire diameter / polarity 1,6 mm			Wire diameter / polarity 2,4 mm		
	DC + 30 - 31 V [gr/min]	DC - 33 - 34 V [gr/min]	current density [A/mm²]	DC + 30 - 31 V [gr/min]	DC - 33 - 34 V [gr/min]	current density [A/mm²]
200	73	83	100			
250	84	110	125			
300	109	150 Accept.	150	94	125 Accept.	66
350				109	151	77
400				125 NOT Accept.	180	88

- ☐ LNS NiCro 60/20 (1.6 mm)-P2000 provides very good mechanical and economical results.
- ☐ Heat inputs from 0.5 to 3 kJ/mm can be used for all welding processes.
- ☐ An interpass temperature of maximum 150°C shall be respected.
- ☐ Welders shall be properly trained and learn to follow the respective WPQ.
- ☐ Intermediate cleaning is recommended, use proper tools such as stainless steel wire brushes, non-pressed alumina grinding discs, power tools with tungsten-carbide tool steel.
- ☐ The welding consumables should be handled and stored as per the supplier's recommendations.

4 Applications

Over the last three decades Lincoln Smitweld has been involved in many projects where 5 and 9% nickel steel has been successfully applied, as for example in LNG storage tanks for onshore facilities as well as for integration into ships. The electrode for SMAW is Nyloid 2, with 150% recovery for welding in a very economical way and in all positions. Over 300,000 kg of Nyloid 2 has been produced and successfully applied in cryogenic applications all over the world. For SAW the wire/flux combination LNS NiCro 60/20 with P2000 has been used extensively. Both welding consumables meet the actual industrial specifications and mechanical properties [16; 17; 18].

One of the most interesting projects in recent years is the Dabhol LNG Terminal Project-Phase II which includes an LNG storage and re-gasification facility for the new power station at Dabhol on the west coast of India. That project has been designed, built and commissioned by Skanska Whessoe. Fig. 8 gives a nice overview of the Dabhol construction site where the three 9% Ni tanks clearly stand out. Figs. 1 and 2, as already referred to, show details during the construction phase of the full containment storage tanks with 9% Ni steel inner shell, a concrete outer shell with bottom corner thermal protection, insulated base protected by secondary bottom system. The concrete base is provided with a base heating system, the bottom insulation is foamglass and the shell insulation in the inter-space is perlite and a resilient fibreglass blanket. The suspended deck is insulated by fibreglass. These tanks have a capacity of 163,000 m^3 each. This required a tank with an inside diameter of 75 m and a height of minimal 37 m. To provide sufficient strength the wall thickness in this case starts with 27.5 mm for the first of the eleven courses through to 10 mm for the last four courses. The project was successfully commissioned in 2001.

In 2000 the Nyloid 2 has been supplied for all the constructions of cryogenic storage tanks in 5% Ni steel that would be placed in a ship. This was carried out on a shipyard in Shanghai, China.

In 1999/2000 the Nyloid 2 was supplied in vast quantities to do repairs in LNG tanks onboard the LNG carrier "Mystic Lady". This work was carried out on a shipyard in Singapore.

In 2001 the Nyloid 2 was supplied for a huge LNG tank-farm project in the Middle East.

In 2002 the Nyloid 2 was used extensively for a LNG terminal project in Portugal.

In 2003/2004 the Nyloid 2 was used for a LNG terminal project in Norway.

In 2004 the Nyloid 2 was used for a LNG terminal project in Spain.

In 2004/2005 the Nyloid 2 was used for a LNG terminal project in Spain.

These are just a few of the projects that Lincoln Smitweld and Lincoln Electric have been involved in over the last 30 years.

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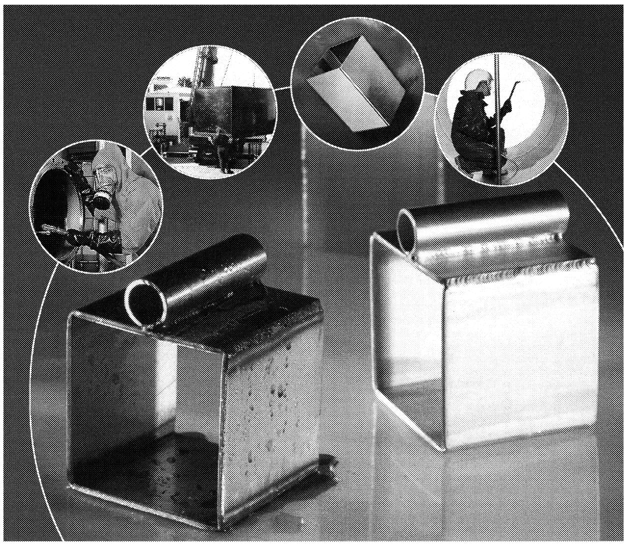

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