Welding Technology for Liquefied Natural Gas Tanks

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Abstract. Liquefied natural gas (LNG) is of great importance in the energy segment of the economy. Natural gas, has a higher calorific value, better fuel efficiency and is more environmentally friendly, thereby gaining more importance compared to oil and coal. Not only does LNG offer greater flexibility in supply, it also has cost advantages for transportation starting from a distance of 2,000 km (at sea) and 4,000 km (on land) respectively. Consequently, the LNG market will grow in the coming decades compared to two other fossil sources - oil and coal. To use natural gas, it is necessary to create safe and economically profitable transportation routes from natural gas deposits to end users. One possibility is to transport gas in a liquefied state, at low temperatures. To ensure safe and reliable storage of liquefied gas at minus 163 °C, good physical and mechanical properties of the base material and weld (corresponding tank system) are required. To meet these high requirements, appropriate welding technologies and welding materials are selected. The paper presents an analysis of activities on the development of new welding materials and improvement of welding technologies for the construction of LNG tanks.

1. Introduction
Chilled LNG storage tanks have been in operation for more than 60 years. Currently, there are two main types of tanks: underground (the largest 200,000 m³) and terrestrial (the largest 180,000 m³). A double-walled structure with an external concrete or reinforced concrete wall is a common type of construction of land-based LNG tanks.

The inner tank is made of 9% nickel steel; heat insulation layer between inner and outer walls prevents temperature compensation. In summer, a temperature difference of almost 200 °C is recorded. An aluminum roof is hung in the roof structure. The concrete tank is further lined from the inside with carbon steel to collect the effluent liquid in the event of leakage. The lower part of the inner coating can also be made of 9% nickel steel (for safety reasons).

For more than five decades, liquefied natural gas (LNG) storage facilities have been built of 9% ASTM A 353 nickel steel to ensure sufficient strength and structural integrity at -163 °C and below [2]. Although studies have been carried out with suitable welding materials for welding these surfacings, it has now been proven that only nickel-based consumables meet the physical and mechanical requirements.

This article will provide a more detailed description of the composition of 9% nickel steel, nickel-based welding materials and welds for chemical composition, heat treatment, mechanical properties, physical properties, international specifications and project requirements for LNG tanks [1-9]. Some
practical recommendations and examples of recent projects on welding of 9% nickel steel by arc welding and arc welding under flux will be presented.

2. Experimental procedures
By liquefying the gas, its volume is reduced by about 600 times, which makes it much easier and more economical to handle and store in storage facilities of reasonable size on land or on ships. Liquefied natural gas (LNG) can be produced by cooling methane gas to a minimum temperature of -163 °C.

At such extremely low temperatures, standard ferrite structural steels are not suitable, due to insufficient strength and the risk of brittle fracture of steel. For this reason, ferrite steels cannot be used in pressure vessels with operating temperatures below -101 °C. Cryogenic 9% nickel steels have been developed to achieve the mechanical properties necessary to create tanks and spherical storage vessels that provide reliable structural integrity at temperatures up to -196 °C.

The determined transition temperature present in ferrite steel disappears when up to 9% nickel is added to ASTM A 353 steel. This significantly reduces the risk of brittle steel fracture. 9% ASTM A 353 nickel steel is widely used for LNG storage worldwide.

2.1. Heat treatment
Heat treatment is key to success, allowing for the desired microstructure with appropriate mechanical properties. Good strength and toughness at low temperatures are present in a microstructure containing nickel-rich ferrite and stable high carbonaceous austenite. This can be done using: double normalization and quenching (NN + T), quenching and tempering (Q + T). Double normalization is carried out at a temperature of about 800 and 900 °C to obtain a uniform structure.

Quenching in water or cooling in air from 800 °C provides a structure with low-carbon martensite and bainite, the hardness of which rarely exceeds 400 BB (high viscosity).

Subsequent tempering at a temperature of about 570 °C, which is slightly higher than the lower critical temperature, leads to the formation of a structure.

Currently, LNG storage tanks are constructed in accordance with the "dual integrity concept," which means that the tank consists of an inner shell of cryogenic steel and an outer shell of concrete [4]. The insulation of the housing in the space between the two shells consists of a strong insulation such as perlite and a resilient glass fiber coating.

This type of design ensures that liquefied gas will be retained within the outer shell in case anything happens to the cryogenic inner shell.

Such tanks usually have a capacity of 163,000 m³ each. This requires a tank with an internal diameter of at least 75 m and a height of at least 37 m. To ensure sufficient strength, the wall thickness in this case begins with 27.5 mm for the first layer.

2.2. Investigation of the process of nickel impact on steel
The main contribution of nickel to steel consists in significant improvement at cryogenic subzero temperatures [7]. Nickel is also very effective in improving the hardenability of steel because it reduces the critical cooling rate required to impart hardening strength. This facilitates the possibility of heat treatment.

Combining the increased nickel content with proper heat treatment, such as normalization or quenching, with subsequent tempering, will significantly increase the toughness and significantly reduce the transition temperature to -196 °C. Figure 1 shows the effect of different nickel content on the low-temperature toughness and transition temperature of normalized low-carbon steels. A practical and cost-effective optimal regime was established in the region of 9% nickel, which is still the basis for modern 9% nickel steels.
Figure 1. Effect of nickel content on low-temperature toughness and transition temperature of normalized low-carbon steels.

ASTM A 353 steel with 9% nickel content was first used in liquid oxygen tanks in 1952, and since then it has been used as the main material of the inner walls of LNG tanks as ferrite steel in ultra-low temperature applications [2]. The brittle fracture properties of steel, which, among other things, are closely related to structural safety, have been carefully studied and as a result, it has become clear that steel and its welds have sufficiently good brittle fracture properties for use in land-based LNG tanks.

The low carbon content of 9% of ASTM A 353 nickel steel guarantees its good weldability and a slight increase in hardness in the thermal zone.

The internal 9% nickel steel tank is constructed of large steel sheets. The dimensions depend on the capacity of the rolled stock and the heat treatment of the suppliers and will therefore differ depending on the supplier.

Thickness of rolling sheet ranges from 10 to 27.5. The stiffness elements of the shell are from 6 to 14 mm, the first bottom is 16.7 mm, and the secondary bottom is 5 mm. All horizontal and vertical seams are butt welded, stiffening elements to the shell are welded by an angular seam, and the secondary bottom is made by overlapping welding due to access on one side.

The preparation of welds can be done by the sheet metal supplier to avoid additional operations and on-site machining. Preparation of welding joints in situ can be done by machining, plasma or gas cutting.

It is recommended to clean the adjacent base metal on either side of the weld. Subsequent cleaning with, for example, acetone is necessary to prevent any contamination of the weld that may cause structural defects.

The ring edge sheets with a diameter of 16.7 mm (the first lower part) are welded in a flat position by means of arc welding with a metal electrode for flexibility, and this can be done by a large number of welders at the same time to increase productivity [3].

The maximum interlayer temperature of 150 °C shall be observed and the heat input of up to 3 kJ/mm is acceptable. An electrode with a diameter of 5 mm and a length of 450 mm contributes to an increase in productivity when filling and passing the facing layer. It is also possible to use arc welding under flux after forming enough weld metal to support arc welding without the risk of burning the weld.

Overlapping welds for a 5 mm thick bottom sheet were made with a high surfacing factor, since the edges are too thin for arc welding under flux.

The requirements for 9% nickel LNG storage tanks are now very stringent and have been increased over the years to make the most effective use of the strength of this material [5-6]. Combining all the specifications for the recent Lincoln projects will give the following mechanical requirements for weld metal of welding materials to be used for welding steel with 9% nickel:

- yield strength > 430 MPa,
- tensile strength: from 690 to 825 MPa,
- material stretching: > 35%, impact (test of a sample with a V-notch for Sharpy toughness): > 70 J at -196 °C,
- transverse expansion: > 0.38 mm at -196 °C,
- viscous component fraction in fracture: > 80% at -196 °C,
- displacement of crack top opening: > 0.30 mm at -165 °C/-196 °C.

Such requirements are met by the steel brand - ASTM A 353 9% Ni, which is widely used abroad.

Depending on the size of the tank, there are from 250 to 350 welds. As a rule, welding work is carried out outdoors or inside a concrete structure. Only pre-assembly of individual tank sections is performed in a large room.

Metal electrode welding in the gas medium (DIN EN ISO 15609-1) is used to manufacture sections. But for welding at the construction site, methods of welding in inert gas cannot be used.

Rod electrodes are used for slanted welds. In addition, rod electrodes are used for the bottom of the tank and for corner welds of annular reinforcement sheets.

Due to the high requirements for welds, 100% X-ray tests are carried out for all welds. If any defects are visible on the radiographic film, for example, non-melting, slag inclusions, cracks, etc., these defects are ground and corrected with a rod electrode with a diameter of 2.5 mm and 3.2 mm. After completion of the repair, the corresponding area is again illuminated with X-rays.

The base metal, a steel with a 9% nickel content, was first used in liquid oxygen tanks in 1952, and since then it has been used as the main material of the inner walls of LNG tanks as ferrite steel in ultra-low temperature applications.

The brittle fracture properties of steel, which, among other things, are closely related to structural safety, have been carefully studied and as a result, it has become clear that steel and its welds have sufficiently good brittle fracture properties for use in land-based LNG tanks.

The low carbon content of 9% of ASTM A 353 9% Ni nickel steel (Table 1) guarantees good weldability and a slight increase in hardness in the thermal zone.

| Steel grade          | Element content, wt% |
|----------------------|----------------------|
|                      | C  | M  | Si  | Ni  | P  | S  |
| ASTM A 353 9% Ni    | <10 | <0,3-0,8 | <0,35 | <8,5-10 | <0,02 | <0,01 |

Optimum parameters of 9% nickel steel are achieved by very precise temperature control during production and controlled quenching. Preheating is performed only if high humidity is condensed on parts or welding works are carried out at temperature below 5 °C [1, 16-19].

During the treatment, steel with 9% nickel content is easily magnetized, which leads to difficult problems in the welding process. Steel should be welded in demagnetized state with maximum residual magnetization of 0.005 Tesla. Work with sheet steel should be done by mechanical clamping devices, and not using magnets for movement.

Tempering by heat treatment in the + range of the lower critical temperature allows nickel to stabilize austenite. In the hardened martensitic matrix, small amounts of high-carbonaceous nickel austenite are formed, in percent by volume from 5 to 10 vol.% which remain stable at cryogenic temperatures equal to -196 °C.

For steel with 9% nickel content, the microstructure of the ringed zone in the welded joint will always be martensitic, even at very low cooling rates (in air) [10-15].

High purity and absence of impurities provide toughness at low temperatures and crack stopping properties, but also eliminate the risk of release brittleness, which positively affects the weldability of 9% nickel steel.
For arc welding with a melting electrode with protection of the welding area, coated rod electrodes are used (DIN EN ISO 15609-1).

During welding, electrode wire and alloying elements of coating are melted to alloyed built-up metal. Nickel-based materials are used due to their high tensile strain of more than 35%, with tensile strength values of more than 700 MPa.

Arc welding with a flux-coated metal electrode (DIN EN ISO 15609-1), a very flexible method of welding, and the method of arc welding under flux (DIN EN ISO 15609-1) is very effective due to the high electrode utilization.

Thus, only an adequate metallurgical alloy methodology can be used.

Welding materials shall be checked in accordance with the specifications before being used for the LNG project.

3. The results of studies and their discussion

LNG storage tanks are being built around the world to meet the constant need for an environmentally friendly energy source. The studies made it possible to determine the influence of the chemical composition and thermal treatment on the strength properties of ASTM A 353 steel, to analyze the existing methods of weldability of parts, assemblies and equipment operated under low temperatures.

4. Conclusions

Based on the analysis, it is recommended to develop and implement projects in the field of transport and storage of liquefied natural gas.

5. References

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