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SOME TECHNOLOGICAL PECULIARITIES OF PERFORMANCE OF ASSEMBLY-WELDING WORKS IN CONSTRUCTION OF ISOTHERMAL TANKS

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The paper deals with the main technological features which should be taken into account during design, fabrication and mounting of tanks from 9 % Ni steel for liquefied natural gas storage. They include preparation for welding, selection of welding processes and consumables, modular assembly of the tank in site, application of ultrasonic peening of welded joints for stress relieving. 8 Ref., 6 Tables, 5 Figures.

Keywords: *arc welding, isothermal tanks, 9 % Ni steel, design, fabrication, mounting, modular assembly, ultrasonic peening*

Isothermal tanks are quite extensively used for liquefied gas storage. The liquefaction allows a significant reduction of gas volume at its transition from the gaseous state into the liquid state. For instance, the natural gas volume decreases more than 600 times. Isothermal tanks are double hull, the inner tank being in direct contact with the product, stored at a low temperature. This means that special attention should be given to the material, from which it is made, as well as to performance of assembly-welding operations during its construction.

Table 1 [1, 2] gives the required temperatures of liquefaction of different gases and appropriate materials for construction of facilities for storage and transportation.

The interest to use of natural gas as an energy source is growing constantly. More and more new natural gas fields are found every year, and on the global scale 4 times more gas is produced than consumed. As the fields (countries of the Persian Gulf, Central Asia, Alaska, Arctic shelf) and the industrial centers of gas consumption (Europe, Japan, North America) are significantly removed from each other, natural gas has to be transported to very large distances, and its greater part should be stored in isothermal tanks in the liquefied state.

Table 1. Gas liquefaction temperatures and materials applicable at these temperatures

Gas	*T*, °C	Base metal grade
Ammonia	–33.4	Carbon steel
Propane	–42.1	Deoxidized fine-grained steel
Propylene	–47.7	Steel with 2.25 % Ni
Carbon disulphide	–50.2	
Carbon dioxide	–78.5	Steel with 3.5 % Ni
Acetylene	–84.0	
Ethane	–88.4	
Ethylene	–103.8	Steel with 5–9 % Ni
Methane (natural) gas	–163.0	
Oxygen	–182.9	
Argon	–185.9	

Materials for construction of LNG tanks should have low-temperature toughness. According to SEW 680**,** steels with low-temperature toughness are those which preserve the fracture energy of at least 27 J at impact toughness testing at temperatures below –10 °C, and according to DIN 17280 the ultimate value of low-temperature toughness is specified at the temperature of –60 °C.

Moreover, the materials should have high strength that will allow reducing the vessel wall thickness and ensuring welding without the risk of brittle fracture. High-alloyed and special materials were applied up to now. They include austenitic welding consumables, nickel alloys, aluminium alloys, copper and copper alloys. As the scope of applications in cryogenic engineering is growing continuously, and the above-mentioned materials are very expensive, the need arose for development of less expensive low-alloyed steels. These most often are nickel steels with different content of nickel, depending on operating temperature.

As the temperature of liquefied natural gas is equal to –163 °C, 9 % Ni steel is a suitable material for manufacturing isothermal tanks for liquefied natural gas, which provides a good combination of properties at an acceptable price.

Table 2. Requirements to 9 % Ni steel to ASTM and JIS

Standard	ASTM		JIS G 3127	
	A353	A353 (Type I)	SL9N 520	SL9N 590
Maximum thickness (mm)	50	50	50	100
Heat treatment	NNT^{*1}	Improved	NNT	Improved
C (%)	≤ 0.13		≤ 0.12	
Si (%)	0.15–0.40		≤ 0.30	
Mn (%)	≤ 0.90		≤ 0.90	
P (%)	≤ 0.035		≤ 0.025	
S (%)	≤ 0.035		≤ 0.025	
Ni (%)	8.50–9.50		8.50–9.50	
Yield limit (MPa)	≥ 515	≥ 585	≥ 520	≥ 590
Ultimate strength (MPa)	690–825		690–830	
Relative elongation (%)	≥ 20.0		≥ 21 (6 ≤ t ≤ 16)^{*2} ≥ 25 (t > 16)^{*2} ≥ 21 (t > 20)^{*3}	
Impact toughness at –192 °C	≥ 34		≥ 34	≥ 41
Lateral expansion at –196 °C	≥ 0.38		–	

^{*1}NNT — two times normalized and quenched.

^{*2}Flat sample No.5, according to JIS Z 2201 (50 mm measuring length).

^{*3}Round sample No.4, according to JIS Z 2201 (50 mm measuring length).

Exceptional low-temperature properties of impact toughness are the result of producing super fine-grained structure of strong nickel ferrite. Small quantities of residual austenite, formed at tempering, improve the impact toughness after heat treatment. Alongside good toughness, resulting from structure improvement, this steel also has higher strength properties.

Table 2 [3] gives information about the chemical composition and mechanical properties of 9 % Ni steel. To ensure good low-temperature toughness this steel should have high purity, i.e. it should have a low content of phosphorus and sulphur, as well as balanced content of the main alloying elements.

There is a wide range of requirements and standards for design, construction, inspection and servicing of 9 % Ni steel tanks for liquefied natural gas. A number of the respective ASME, API, EN and JIS standards are given below.

1. ASME Sec. VIII, Div.1: Rules for Construction of Pressure Vessels; Div. 2: Alternative Rules.
2. API Standard 620: Design and Construction of Large, Welded, Low-Pressure Storage Tanks, Appendix Q: Low-pressure storage tanks for liquefied hydrocarbon gases at temperatures not lower than –168 °C.
3. EN 14620-1 (2006): Design and manufacture of site built, vertical, cylindrical, flat-bottomed steel tanks for the storage of refrigerated, liquefied gases with operating temperatures between 0 °C and –165 °C. Part 1: General.
4. JIS B8265 (2010): Construction of Pressure Vessels — General Principles; JIS B8267 (2008): Construction of Pressure Vessels.

Factors influencing welding of 9 % Ni steel. Successful welding of 9 % Ni steel at preservation of its low-temperature toughness depends on a number of factors, which are:

- production method and grade of supplied steel;
- base metal properties, residual magnetism, susceptibility to arc magnetic blow, heat conductivity and thermal expansion;
- welding process;
- welding heat input;
- cooling rate, dependence on preheating temperature and interpass temperature.

Preparation for welding. Nickel steels with low-temperature toughness are prone to preservation of residual magnetism that has a negative effect on their behaviour during welding, because of appearance of magnetic arc blow. Therefore, it is necessary to perform their welding in demagnetized condition. When ordering steel supply, alongside the certificate of compliance with EN 10204 «Certification of materials», it is also necessary to specify the inspection of magnetic field strength, which should not exceed the average value of $20 \cdot 10^{-4}$ T. This guarantees the magnetic field not influencing the welding process, particularly in welding the tubular or cylindrical elements.

Welding processes and welding consumables. The following methods are used for welding 9 % Ni steel: coated electrode manual electric arc welding, flux-cored wire welding, submerged-arc welding, TIG and MIG welding. Selection of welding consumables for these steels depends on a number of factors: safety, calculation of product design and cost effectiveness.

Product safety is determined by the following properties of welding consumable: thermal expansion coefficient, hydrogen sensitivity, hot cracking resistance, impact toughness, crack propagation, relative elongation after rupture (tensile strength) at tensile deformation, behaviour from the viewpoint of fracture mechanics.

Product design should take into account the following: yield limit, strength and impact toughness at design temperature.

Cost effectiveness requires taking into account such factors as welding methods, efficiency of welding consumable application, repairability, and welding consumable cost.

Characteristics of individual groups of welding consumables. *Welding with matching consumables.* This group covers welding consumables with 9 % Ni. Welding with matching welding consumable is not recommended for critical structures, as it cannot guarantee sufficient impact toughness of weld metal.

1. Chromium-nickel austenitic welding consumables (Cr–Ni alloying type). They provide good ultimate strength and yield limit of weld metal. Weld metal has high impact toughness at temperatures above –196 °C.

2. Nickel alloys. This variant is preferable due to greater stability of weld metal at variable temperatures.

Nickel-based welding consumables, such as Inconel (Ni–Cr alloy) and Hastalloy (Ni–Mo alloy), have almost the same linear expansion coefficient, as 9 % Ni steel, whereas austenitic welding consumables have linear expansion coefficient, different from that of 9 % Ni steel. If this peculiarity is ignored, there is the risk of thermal fatigue, resulting from different thermal expansion. Nickel-based welding consumables provide a lower crack propagation rate.

Specification and properties of welding consumables. Table 3 [3] gives the requirements of AWS and JIS specifications to welding consumables for 9 % Ni steel.

Coated electrodes. In keeping with AWS-A5.11 specification, the following types of coated electrodes are recommended: EniCrFe-9, EniCrMo-6 and EniMo-8, and according to JIS Z 3225: D9Ni-1 and D9Ni-2.

Flux-cored wires. Application of flux-cored wire for welding LNG tanks from 9 % Ni steel is limited because of stringent control of welding parameters in a narrow range to avoid hot cracking, and welding in all the positions is difficult.

TIG-welding with mechanized feed of solid wire. It is mostly used in Japan.

The main advantage of TIG welding is the possibility of automatic welding application at higher values of current and intentional magnetic deviation of the arc to produce high-quality weld metal. This welding method is two times more effective than coated-electrode welding and four times more effective that manual TIG welding. More over, this method allowed reducing defects almost to zero, and improving the welding time, total cost and weld quality.

Submerged-arc welding. In specifications for submerged-arc welding in A 5.14 AWS only the wires are regulated. Contrarily, JIS standard specifies a combination of wire and flux. It is shown in Table 4 [3].

Welding procedures. A key factor in cost-effective and sound design of a tank is reduction of production operations in site. This can be achieved through development of a modular structure, in which each individual module is manufactured in shop conditions, and transported to the assembly site for subsequent mounting. Even the domed cap of the tank for liquefied natural gas is manufactured in the plant as enlarged elements and is joined to the hull in site by its lifting by compressed air.

Welded joints made in site are shown in Figure 1. The procedures of welding individual types of joints are given in Table 5.

Figure 2 gives the examples of beveling of the edges to be welded for different welding methods and welding positions.

Recommendations for obtaining the best results. *Avoiding steel magnetization*. At transportation, storage and further processing, one should avoid material magnetization, which may occur at circular

Table 3. AWS and JIS specifications for welding consumables for 9 % Ni steel

Process	AWS standard	Specifications for
Manual electric arc welding	A5.11/A5.11M:2005	Coated electrodes from nickel and nickel alloys
Flux-cored wire welding	A5.34/A5.34M:2007	Flux-cored wire from nickel alloys
MIG welding TIG welding Submerged-arc welding	A5.14/A5.14M:2005	Solid wire from nickel and nickel alloys
Process	JIS стандарт	Specifications for
Manual electric arc	Z 3225:1999	Coated electrodes for 9 % Ni steel
TIG welding	Z 3332:1999	Rods and solid wire for TIG welding of 9 % Ni steel
Submerged-arc welding	Z 33335:1999	Solid wire and fluxes for submerged-arc welding of 9 % Ni steel

Table 4. Technical requirements for wire (AWS) and fluxes (JIS) for automatic welding

Technical requirements	AWS A5.14 Wire ERNiMo-8	JIS Z 3333	
		FS9Ni-F/YS9Ni flux weld metal	FS9Ni-H/YS9Ni flux weld metal
For chemical composition			
C (%)	≤ 0.10	≤ 0.10	≤ 0.10
Si (%)	≤ 0.75	≤ 1.5	≤ 1.5
Mn (%)	≤ 1.5	≤ 3.5	≤ 3.5
Ni (%)	≥ 60.0	≥ 60.0	≥ 60.0
Cr (%)	0.5–3.5	–	–
Mo (%)	17.0–20.0	10.0–25.0	10.0–25.0
W (%)	2.0–4.0	–	–
Fe (%)	≤ 10.0	≤ 20.0	≤ 20.0
For mechanical composition			
Yield limit (MPa)	–	≥ 365	≥ 365
Ultimate strength (MPa)	–	≥ 660	≥ 660
Relative elongation (%)	–	≥ 25	≥ 25
Impact toughness *KCV* at –196 °C	–	Average value ≥ 34 Each sample ≥ 27	Average value ≥ 34 Each sample ≥ 27

Table 5. Welding procedures for individual joint types (see Figure 1)

Joint number	1	2	3	4
Element	Hull	Hull	Bottom to hull	Bottom
Joint type	X-shaped asymmetric	X-shaped asymmetric	X-shaped asymmetric	Overlap
Position	Vertical	Horizontal	Horizontal	Horizontal
Welding process	Coated electrodes with flux-cored wire Auto-TIG	Submerged-arc Auto-TIG	Coated electrode Auto-TIG	Coated electrodes with flux-cored wire Auto-TIG

bending between the rolls; at transportation by magnetic cranes; at cutting with guidance along magnetic rollers; under the impact of current-conducting welding cables or at other similar impacts. Before welding, the magnetic field between the edges being welded should be controlled by a magnetometer. Values of magnetic field intensity up to $60\cdot10^{-4}$ T do not have any significant effect on welding.

One of the following measures can be proposed to solve the problem of magnetic blow:

- alternating current welding;
- use of modern welding current sources, for instance square-wave source, etc.;
- deposition of a buffer layer on the edges to be welded with an electrode selected for welding;
- after occurrence of magnetization it can be reduced or eliminated by applying conductors (cables), through which alternating current runs, or using electric magnets. Thicker sheets may require application

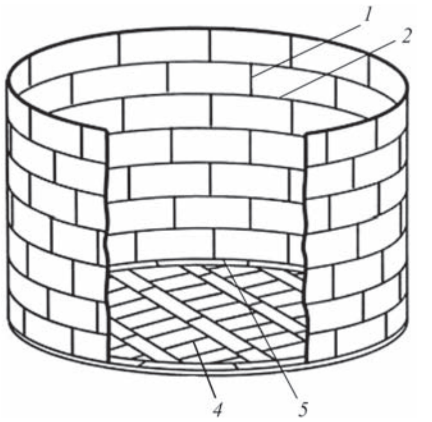

Figure 1. Typical welded joints of the hull and bottom of 9 % Ni steel tank made in site conditions (for description of *1*–*4* see Table 5)

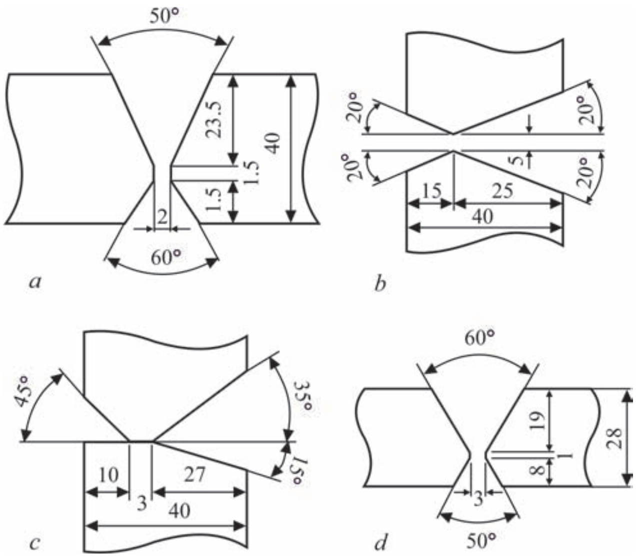

Figure 2. Typical groove for different welding methods and positions: *a* — SMAW; *b* — GTAW; *c* — SAW; *d* — FCAW

of special demagnetization equipment, which uses gradual decrease and change of current direction. In extreme cases, residual magnetism can be eliminated by heat treatment.

Rate of energy input (*heat input*). Similar to other low-temperature steels, it is necessary to control the heat input for preservation of impact toughness in the HAZ metal. As a rule, steel is welded with small heat input — it is best to perform even submerged-arc welding with 1.6 mm wire.

It is recommended to perform welding with the heat input from 1.2 up to 2.0 kJ/mm. Irrespective of the thickness, it is not recommended to conduct welding with more than 2.0 kJ/mm heat input. If higher heat inputs are used for submerged-arc or MIG welding, it is necessary to first make sure that the weld strength is not lower than 655 MPa. Care should also be taken at less than 13 mm thickness, as in welding sheets the joints cool down slower, and, in addition, the values of impact toughness for thinner sheets are initially lower.

Preheating. 9 % Ni steels have relatively good cold cracking resistance. Irrespective of that, it is recommended to preheat plates of more than 25 mm thickness up to 35 °C, and not to weld thinner sheets at temperature below the dew point. The interpass temperature should not exceed 150 °C.

Postweld heat treatment. If not specifically recommended by the manufacturer, postweld heat treatment is not performed on up to 51 mm thicknesses. To avoid the possible lowering of steel impact toughness during heat treatment performance, after welding it is necessary to control the temperature in the range of 551–583 °C, but not higher than that of tempering with subsequent cooling at not less that 167 °C/h rate.

Hot cracking. As a rule, it concerns hot cracks in the crater. It is recommended to grind off the crater every time you stop the arc.

Base metal participation. Mechanical properties of weld metal depend on the quantity of base metal, participating in the weld metal. This most often influences lowering of mechanical properties. It is recommended to first check the effect of welding parameters, developing a procedure that would ensure the required ultimate strength and yield limit of weld metal.

Table 6. ISO requirements to impact toughness of samples with V-shaped notch

Material grade	Testing temperature, °C	Fracture energy*, J (min)	
		Along the rolling direction	Across the rolling direction
Sheets	–20	–	27
Pipes		41	–
Forgings		41	27

*Average value. One of the values can be lower than the average value; but not lower than 70 % of its value.

Isothermal tanks for liquefied ammonia storage. It was found that stress corrosion cracking is one of the main causes for accidents in anhydrous ammonia tanks under normal service conditions [3]. These cracks propagate predominantly inside the crystalline grains and are usually observed in steels with higher strength and hardness.

Observations show that cracks are most often associated with welded joints, where HAZ hardness is higher than that of base metal and weld metal, and tensile residual stresses are in place. Performance of postweld heat treatment for relieving residual stresses reduces the cracking susceptibility [4], but it often cannot be conducted, because of large dimensions of the tanks. Moreover, heat treatment after commissioning of the facility can be ineffective, as the stress fields at the tip of the initiating cracks have quite high intensity, which supports crack propagation.

Measures required for designing tanks for ammonia storage. Factors promoting formation of stress corrosion cracking can be divided into three groups:

Tank material. From the viewpoint of material the following factors should be taken into account: material type, mechanical properties and chemical composition, microstructure, deformations and surface condition. Plates from low-carbon low-alloyed steel with nominal yield limit not higher than 355 MPa are recommended for manufacture [5] of tanks for anhydrous ammonia. Actual yield limit should not exceed 440 MPa, and relative elongation δ_5 should be higher than 22 %.

It is recommended that the chemical composition is in the following range, wt.%: 0.18 C; 0.10–0.50 Si; 1.65 Mn; 0.030 P; 0.025 S; min 0.020 Al; 0.20 Cr; 0.35 Cu; 0.08 Mo; 0.40 Ni; 0.10 V. After normalizing the steel should have a fine-grained structure. It should be taken into account that for steels with nominal yield limit of 355 MPa the chemical composition is selected in order to limit the maximum yield limit to 440 MPa. If alloying with nickel is required, the maximum value can be 0.85 %.

All the pressure vessel materials should meet the requirements to impact toughness, according to Table 6.

Active medium. In terms of active medium, the following should be taken into account: medium type, impurities, temperature and electrochemical conditions.

Anhydrous ammonia is stored at temperature in the range from ambient temperature to –33 °C. Crack formation during stress corrosion greatly depends on presence of oxygen and water in ammonia. In all the cases, crack formation is associated with oxygen presence. Cracking susceptibility becomes higher with

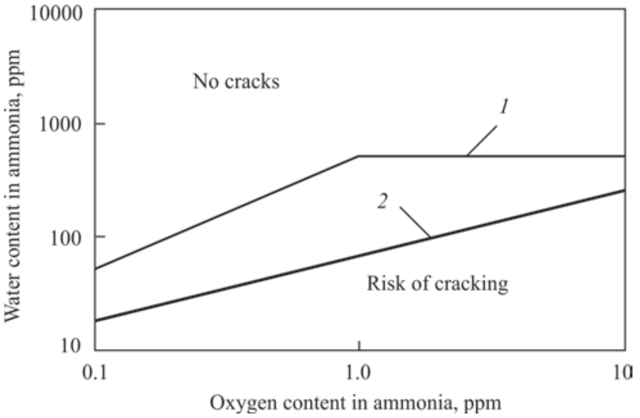

Figure 3. Relationship between water and oxygen content in ammonia and risk of crack formation during stress corrosion [6] (*1* — 18; *2* — –33 °C)

increase of oxygen content and decreases with water content (Figure 3). Usual practice is use of water as corrosion inhibitor.

Under normal working conditions of a cooled ammonia tank, oxygen content should be lower than 0.5 ppm, and water content should be in the range from 100 up to 1000 ppm.

Stresses. In terms of stresses, the following should be taken into account; residual stresses, resulting from the production process when building the construction, in particular welding stresses, working stresses and such kinds of stresses as static and cyclic, arising in service. Surface tensile residual stresses have a special role in stress corrosion cracking. For this reason, serious attention should be given to means for their reduction.

Features of welding technology, ensuring maximum fatigue life of welded structure. To achieve maximum fatigue life of ammonia tanks, it is necessary to comply with a number of conditions in development and introduction of welding technology, concerning selection of welding consumables and welding mode, in order to avoid stress corrosion cracking.

For manual electric arc welding, it is necessary to use coated low-hydrogen basic electrodes (diffusible hydrogen content below 8 ml/100 g). It is allowed to apply only welding consumables, containing no molybdenum or vanadium. Strength of deposited material should exceed that of the base metal by a minimum value. Weld hardness, including the heat-affected zone, should not be higher than *HV* 230. This should be confirmed at testing and approval of the procedure.

Preheating temperature should be minimum, in order to maintain low welding stress and welded joint hardness. Preheating and interpass temperatures should be not lower than 100 °C, and all the welding operations should be performed by a multilayer welding technique.

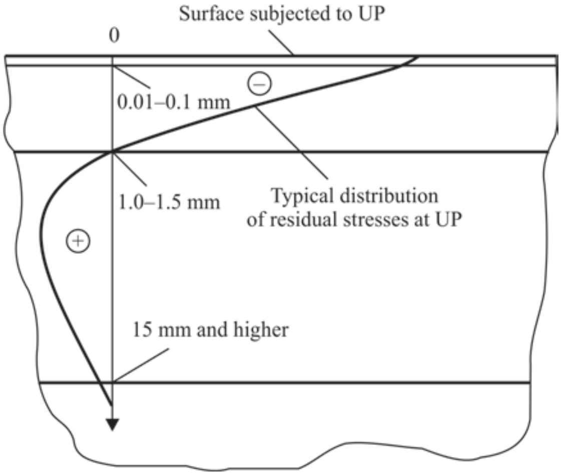

Figure 4. Scheme of the cross-section of material/item, improved by ultrasonic peening [7]

Welding defects, such as excessive weld reinforcement and points of striking (the arc) on the base metal should be eliminated by grinding off. All the butt welds and welds with full penetration of the tank wall should be made by multilayer technique.

In a specific case a suitable method for relieving residual stresses is the ability to perform their ultrasonic peening. If required, the weld surfaces should be ground.

Ultrasonic peening. Ultrasonic peening (UP) is an effective method of relieving harmful tensile residual stresses and generation of favourable compressive residual stresses in surface layers of parts or welded elements. UP method is based on a combined effect of high-frequency shocks applied by special strikers and ultrasonic oscillations in the treated material. During ultrasonic treatment the striker oscillates in a small gap between the end face of ultrasonic converter and treated sample, striking at the surface being treated.

Ultrasound has the following effects on the metal: acoustic softening (hardness lowering), acoustic strengthening, acoustic heating, etc. In the first case (acoustic softening, so-called acoustoplastic effect), acoustic radiation reduces the stress that is required for plastic deformation.

Figure 5. System for ultrasonic peening, increasing the fatigue life of welded elements and structures [8]

On the whole, influence of ultrasound on the mechanical behaviour can be compared with the effect of material heating. The difference consists in that the acoustic softening occurs directly after the impact of ultrasonic irradiation on the metal. Moreover, ultrasonic waves with relatively small amplitude do not have any residual effects on the physical properties of metals after exposure to acoustic radiation.

At UP the ultrasonic converter (piezoelectric or magnetostriction) oscillates at a high frequency, typical frequency being 20–30 kHz. Irrespective of the technology of converter manufacturing. its end face will oscillate with 20–40 mm amplitude.

UP can provide an increase of resistance to stress corrosion cracking by inducing compressive residual stresses in the surface layers of metals and alloys, reduction of stress concentration in the heat-affected zone, and improvement of mechanical properties of the material surface layer. Figure 4 shows the scheme of the cross-section of material/item, treated by UP.

Figure 5 shows the configuration of the device for ultrasonic peening, which can be used for processing of both the weld HAZ and large surface areas, if required [7]. Treatment speed is about 0.4 m/min.

Control of residual stresses. After treating the structure to relieve or lower the residual stresses, it is necessary to find out the degree of this treatment effectiveness and efficiency. There are two groups of methods for residual stress measurement: destructive and nondestructive. The first group of methods (destructive) is not applicable for control of ammonia tanks.

The nondestructive group of testing methods include magnetic, ultrasonic, and X-Ray diffraction. Ultrasonic testing methods are quite promising. They are based on acoustoelastic effects, as a result of which the speed of elastic wave propagation in solids depends on mechanical stresses [7].

In conclusion it should be noted that the high operational reliability of the tanks for storage of liquefied natural gas can be ensured at comprehensive compliance with the requirements at the stages of design, manufacture, mounting and service.

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