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TECHNICAL PARAMETERS AND FEATURES OF MANUFACTURING HIGH-PRESSURE VESSELS FOR NATURAL GAS TRANSPORTATION

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Considered are the technical capabilities of simplified manufacture of all-metal high-pressure vessels for delivery of natural gas through application of prefabricated 351–610 mm pipes from higher strength steels. Dimension-weight parameters and stresses in the vessel wall, depending on steel strength, are determined. The structure, structural-mechanical inhomogeneity and fatigue resistance of the welded joints were examined. Elimination of rolling, welding, thermomechanical treatment, heat treatment of the shell from the technological process and formation of outer fiberglass casing, as well as reduction of wall thickness, diameter and weight provides significant simplification of vessel manufacture, reduction of the number of passes, time of welding the circumferential welds, and power consumption. 25 Ref., 1 Table, 5 Figures.

Keywords: *all-metal high-pressure vessels, pipes, stresses, welded joints, structure, mechanical properties, cyclic fatigue life, dimension-weight characteristics*

One of the kinds of natural gas delivery is its marine transportation by ships under the pressure of 20–30 MPa in cylindrical steel and metal plastic vessels, made with application of gas pipes of a large diameter (1020, 1029, 1067, 1219 mm) with up to 40 mm wall thickness from steel of X80 grade [1–5]. It is proposed to perform gas delivery to Ukraine in metal plastic vessels of 390 and 1020 mm diameter and 5.8 and 11.7 m length [1, 6]. They are manufactured with application of rolling, welding of longitudinal joints, thermomechanical and heat treatment of the shell from 30KhGSA steel [7], or using X80 steel pipes [8] and forming the outer fiberglass casing. Application of large diameter pipes from high-strength low-alloyed steels was proposed for manufacturing metal plastic vessels for rapid supply of compressed gases to small enterprises, farms, etc. [9].

In view of the possible instability of gas imports, it is urgent to arrange delivery of natural gas in simplified mobile vessels, production of which can be quickly mastered. Manufacturing all-metal large diameter vessels with greater wall thickness and metal plastic vessels reinforced by fiberglass casing of approximately three times greater thickness than that of the body wall [10], is quite complicated for the modern technical condition of Ukrainian industry.

The objective of the work was determination of the feasibility and evaluation of the effectiveness of simplified manufacture of high pressure vessels for delivery and storage of natural gas with the prospect of possible rapid mastering of their production. It is achieved by elimination from the technological process of forming of the fiberglass casing and manufacturing of the heat-treated shell due to application of prefabricated pipes of medium diameter, including heat-treated pipes, with wall thickness not greater than that of the wall (9.1 and 13.5 mm) of the bodies of metal plastic vessels of a large diameter (1020 mm).

An all-metal vessel consists of equal-thickness shell of medium diameter pipe from higher strength steel and two convex bottoms with branch pipe and union, in at least one of them, which are butt welded by circumferential welds. Pipes of 426 mm and greater diameter, produced in Ukraine with application of arc welding, can be manufactured from sheet steels of X80 and X100 grade. Such steels, alloyed by 1.6–1.9 % Mn and microalloyed with Ni, Cr, Mo, Ti, V, Nb, after thermomechanical treatment, including controlled rolling and accelerated cooling, as well as other kinds of treatment, are characterized by higher strength ($\sigma_t \geq 625$ and 760 MPa), ductility ($\delta_5 \geq 18$ and 17 %) and toughness ($KC_{-40} \geq 155$ and 160 J). Lowering of the content of carbon to 0.03 % and of sulphur to 0.01 % ensures increase of ductility, deformability and toughness, and improvement of weldability, compared to alloyed carbon steel [11–13].

Seamless hot-deformed pipes of 530 (550) mm and smaller diameter are manufactured from 30KhGSA steel with $\sigma_t \geq 686$ MPa and $\delta_5 \geq 11$ %. At customer's request they shall be made heat-treated. Such pipes are given in the list of materials, used for manufacturing pressure vessels [14].

The main technical parameters of the considered all-metal vessels 11.4–11.6 m long, proposed for natural gas delivery (as a possible variant), are given in the Table. They were determined with application of formu-

Dimension-weight parameters and stresses in the wall of steel vessels of 11.4–11.6 length at P_w = 20 MPa

Parameters	Pipe and vessel steel											
	X80 σ_t = 640 MPa		30KhGSA with HT σ_t = 960 MPa		30KhGSA without HT σ_t = 700 MPa				X100 σ_t = 800 MPa			
D, мм	508	426	530	508	530	426	377	351	610	558	508	426
S, мм	13.2	11.1	9.4	9.0	12.7	10.2	9.0	(8.5)	12.8	11.7	10.7	9.0
D/S	38.5	38.4	56.4	56.4	41.7	41.8	41.9	41.3	47.6	47.7	47.5	47.3
K	1.75	1.75	1.76	1.76	1.76	1.76	1.75	1.78	1.75	1.75	1.76	1.76
[σ], MPa	365.7	365.7	545.5	545.5	397.7	397.7	400.0	392.9	457.1	457.1	454.5	454.5
σ_w^h, MPa	364.8	363.8	543.8	544.4	397.3	397.6	398.9	392.0	456.6	456.9	454.7	453.2
σ_w^m, MPa	177.5	177.1	267.0	267.3	193.8	193.9	194.6	191.6	223.4	223.6	222.5	221.7
V, m^3	2.06	1.44	2.33	2.14	2.27	1.45	1.14	0.985	3.06	2.55	2.11	1.47
M, t	1.85	1.29	1.40	1.28	1.86	1.19	0.93	0.814	2.19	1.82	1.50	1.05
M/V, t/m^3	0.89	0.89	0.60	0.60	0.81	0.82	0.81	0.826	0.71	0.71	0.71	0.71

las (1)–(5), of which formulas (2)–(3) are given in work [15], and formula (1) is derived from formula (2).

$$S = \frac{K_s P_w D}{2(\sigma_w + K_s P_w)}, \tag{1}$$

$$\sigma_w^h = \frac{P_w(D-2S)}{2S}, \tag{2}$$

$$\sigma_w^m = \frac{P_w(D-2S)}{4(D-S)}, \tag{3}$$

$$V = 0.262(D - 2S)^2(3l_c + 2D), \tag{4}$$

$$M = 24.65S(D - S)(l_c + D), \tag{5}$$

where S, D and l_c are the wall thickness, outer diameter and length of the vessel cylindrical part; K_s is the coefficient of safety of the vessel; P_w is the working pressure of gas in the vessel (20 MPa); σ_w^h, σ_w^m and [σ] are the working hoop, meridian and allowable stresses in the wall; V and M are the capacity and weight of the vessel.

According to DNV Rules for cargo tanks of CNG ships K_s = 1.60–1.80 is allowed [3]. K_s value can be the same for the main pipelines, and at wall thickness of 18.7 mm with a surface defect of 500 mm length and up to 5.3 mm depth it is equal to 1.77–1.80 [16]. Metal plastic vessels are allowed to be manufactured with K_s = 1.70 and 1.75 [1, 17]. Therefore, keeping the safety coefficient of approximately 1.75 for all-metal welded vessels is completely justified.

Minimum diameter of vessels from X80 and X100 steels, given in the Table, is determined by minimum diameter of 426 mm of pipes manufactured in Ukraine with application of arc welding. Calculated wall thickness of 9.0 and 8.5 mm corresponds to minimum diameters of 508 and 351 mm of vessels from 30KhGSA steel. Seamless hot-deformed pipes (heat-treated and non-heat treated) of the given diameters with wall thicknesses smaller than those given above, are not manufactured. In vessels of greater diameters than those given in the Table, wall thickness exceeds that of the body from the same steel in metal plastic vessels.

At application of pipes from X80 steel the vessel wall thickness with the coefficient of safety of 1.75 can be 11.1 and 13.2 mm. Wall thickness of vessels from heat-treated and non-heat treated 30KhGSA steel and X100 steel can be 9.0–9.4; 8.5–12.7 and 9.0–12.8 mm, respectively, keeping the coefficient of safety of 1.75–1.78. Here, vessels from the two latter steels are manufactured in a broader range of diameters of 351–530 and 426–610 mm. Vessel D/S ratio grows linearly with increase of steel σ_t, which is accompanied by decrease of M/V ratio from 0.89 to 0.60 t/m^3 (Figure 1). A similar reduction of M/V occurs almost linearly with D/S increase. Here, the vessels from steel of the same level of strength have the same D/S, σ_w^h, σ_w^m, and M/V values.

Working hoop stresses σ_w^h do not exceed allowable stresses $[\sigma] = \sigma_t/K_s$, and meridian stresses σ_w^m are lower than [σ] 2.04–2.06 times. This eliminates vessel destruction at a constant gas pressure of 20 MPa. Stresses in the wall of hemispherical bottoms are the same as meridian stresses [15]. Therefore, the bottoms can be formed from less expensive unalloyed and low-alloyed widely applied steels, which are used for manufacturing pressure vessels. Their σ_t should not be lower than $0.5\sigma_t$ of the applied pipe steel.

The weight of all-metal vessels in the range of 0.81–1.85 t is much smaller than M = 4.95 and 6.15 t of metal plastic vessels of the same length. This, in combination with smaller wall thickness and diameter, facilitates performance of welding and rigging operations. Their capacity of 0.99–3.06 m^3 is much lower than that of metal plastic vessels of a large diameter. The weight and capacity change synchronously with the change of diameter and length. When all-metal vessels are placed into a container, their total capacity can exceed the total capacity of metal plastic

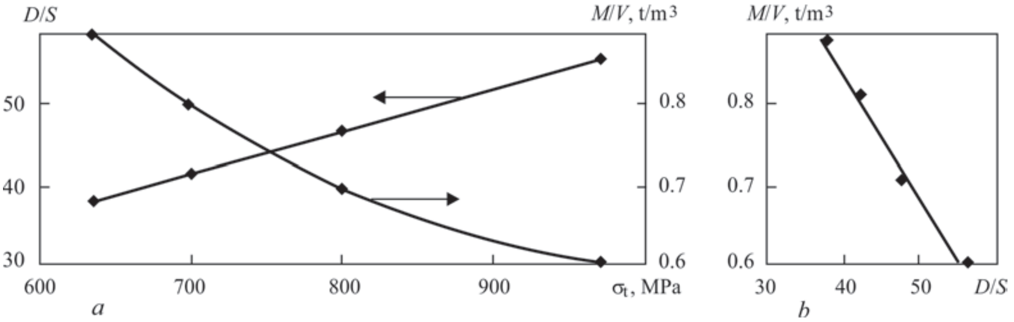

Figure 1. Effect of σ_t of pipe steel on *D/S* and *M/V* (*a*) and *D/S* on *M/V* (*b*) of all-metal vessels of 351–610 mm diameter

vessels, due to absence of the fiberglass casing. The volume of gas in the container is almost independent on the diameter of vessels placed into it.

M/V characteristic is practically independent on the vessel diameter and length, when keeping l_c/D = = 5–7 and higher.

$$M / V = \rho \left[2\frac{K_s p}{\sigma_t} + \left(\frac{K_s p}{\sigma_t} \right)^2 \right]$$

is determined by steel strength, coefficient of safety of the vessel and gas pressure (ρ = 7.85 t/m^3 is the steel density). Practical independence of *M/V* from dimensional parameters of the vessel allows quick assessment of this characteristic, before designing the vessel.

Multipass arc welding from one side of roll-welded butt joints of pipes and bottoms with the wall thickness of 9.0–13.2 mm with U-shaped groove, allowing for [9, 18–20], is conducted with performance of gravity welding of the root pass by consumable electrode gas-shielded arc process, in particular, using CO_2; nonconsumable electrode argonarc welding and coated electrode welding. Small weight of the weld pool in tungsten electrode argonarc welding with activating flux and metal solidification from the side walls (Figure 2), promote prevention of molten metal flowing out and improve formation of the welded joint from the reverse side. Subsequent filling of the groove can be continued by the above-mentioned welding processes. Circumferential joints are subjected to local tempering, in particular with flexible electric heaters.

Multilayer weld metal of experimental butt joints of X80 steel, made by submerged-arc welding, has ferritic-bainitic structure with MAK-phase inclusions (Figure 3), similar to metal of the longitudinal weld of prefabricated pipes [21]. Its higher hardness of *HRB* 88–91, compared to *HRB* 72–75 and 71–72 of the base metal and HAZ is practically preserved after high-temperature tempering (*HRB* 88–89, 71–73 and 70–73).

Microstructure of metal of welded joint on 30KhGSA steel is a mixture of martensite, bainite, as well as ferrite (Figure 4) [22]. In the points of repeated short-time heating below the start of austenitic transformation A_{C_1}, there is a tendency to formation of the structure of tempered sorbite. In the upper part of the joint made by nonconsumable electrode argonarc welding, the metal of the weld and HAZ regions adjacent to it has high hardness *HV*0.2–390–500, which decreases to *HV*0.2–230, when removed from the weld towards the thermally improved base metal with hardness *HV*0.2–280–300 (Figure 5, *a*). Metal in the weld lower part has lower hardness *HV*0.2–260–300, due to tempering at heating during welding. Longer

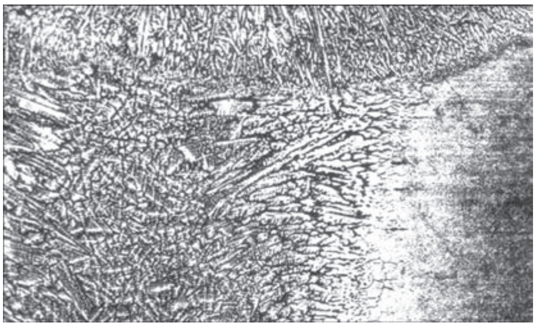

Figure 2. Primary microstructure of metal (×50) of root and subsequent layers of the weld of butt joint

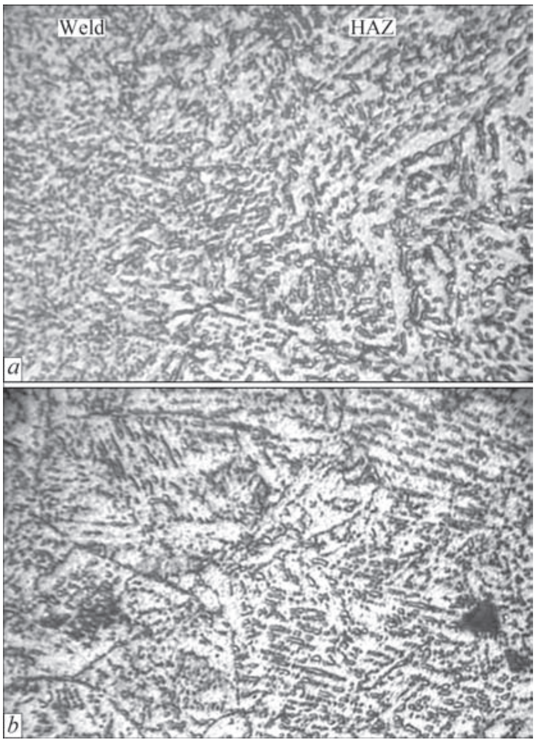

Figure 3. Microstructure (×320) of metal of fusion zone (*a*) and HAZ (*b*) of steel of X80 grade

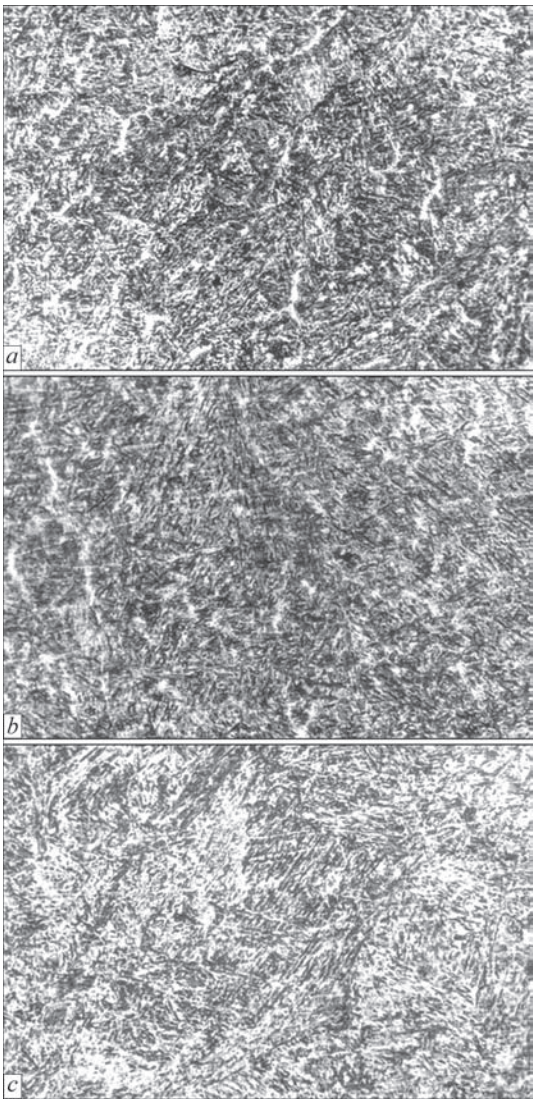

Figure 4. Microstructure (×320) of metal of root (*a*) and subsequent (*b*) layers of weld and fusion zone (*c*) of 30KhGSA steel

postweld local tempering leads to lowering of metal hardness in the weld upper and lower parts to *HV*0.2–330–420 and *HV*0.2–230–240 (Figure 5, *b*). In highly tempered welded joint made with Np-30KhGSA wire in CO_2, a distribution of hardness *HV*0.2–270–330, which is uniform in width and height, is achieved.

Impact toughness KCU_{20} in weld metal of 10Kh2M type and HAZ of test butt welded joints of X80 steel rises slightly from 86 to 87–95 and from 286 to 289–305 J/cm^2 at performance of high-temperature tempering, respectively. Microalloyed manganous weld metal of pipes for the main pipelines has higher value of KCV_{20} = 110–120 J/cm^2 [21]. In highly tempered weld metal of 18KhM type in 30KhGSA steel this value is KCU_{20} = 90.9 J/cm^2. The given impact toughness values of welded joints exceed minimum admissible values of KCU_{20} = 50 J/cm^2 and KCV_{20} = 35 J/cm^2 [14].

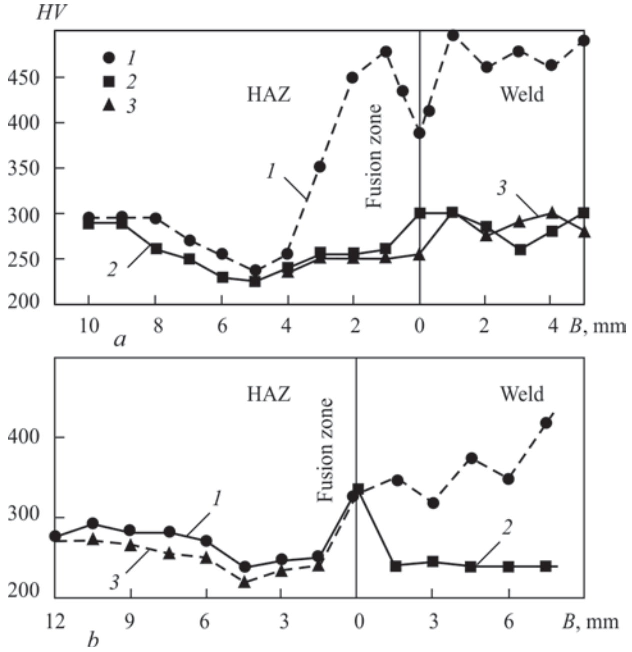

Figure 5. Distribution of microhardness in the upper (*1*), lower (*2*) and middle (*3*) part of a butt joint of heat-treated 30KhGSA steel 10 mm thick after argonarc welding (*a*) and subsequent local tempering (*b*)

Higher strength of weld metal leads to statically tested welded samples failing beyond the weld. Higher strength metal is characterized by higher fatigue resistance. Cyclic fatigue life at tension up to σ_1 = 350 MPa of flat welded samples from X80 steel in the straightened part of a large diameter pipe after submerged-arc butt welding is 86100 cycles to fracture from the point of transition of a weld with approximately 1.5 mm height of reinforcement to the base metal. It rises to 114100 cycles after high-temperature tempering, and at combination of high-temperature tempering with smaller load σ_1 = 300 MPa, it increases to 312400 cycles. Established number of cycles of uniaxial tension to fracture of samples from X80 steel, welded by submerged-arc process, is higher than 5200–7800 cycles of gas filling and discharge 2–3 times per week for 50 years of operation by 11–22 times and more. It is much higher than 15000–24000 cycles of hydraulically tested combined car bottles with heat-strengthened and fiberglass-reinforced body from alloyed steel [23].

With lowering of weld reinforcement height to 0.3–0.5 mm and improvement of welded joint formation at nonconsumable electrode argonarc welding of 30KhGSA steel, the cyclic fatigue life of samples in as-welded and locally as-tempered condition is higher than 217800 and 229200 loading cycles at σ_1 = 350 MPa (fracture along the fillet). After reduction of fillet roughness the welded samples do not fail during 584400 and 674400 cycles at the same load, exceeding σ_w^m = 192–194 and 267 MPa, equal to 0.273–0.278σ_t of non-heat treated and heat-treated steel of seamless pipes. Fatigue limits σ_{-1} of about 0.4σ_t of steel [24] and σ_0 = 0.27–0.30σ_t of welded joints of low-alloyed high-strength steels [25] are higher than σ_w^m, and there is no risk of fatigue fracture of circumferential joints, because of varying gas pressure in the all-metal vessel.

Conclusions

1. The rationality of simplified manufacture of welded high-pressure vessels for delivery of natural gas and supplying gas to small companies is substantiated. This is achieved by application of prefabricated pipes of medium diameter from higher strength steels (X80, 30KhGSA, X100) and elimination of high power-consuming operations for forming the outer fiberglass casing and manufacture of heat-strengthened welded shell from the technological process. Less strong low-alloyed (and carbon high-quality) sheet structural steels are acceptable for manufacture of bottoms of all-metal vessels.

2. Relatively small wall thickness, diameter and weight of the vessels enable simplification of performance of welding and rigging operations, reducing the number of passes and welding time, welding material and power consumption. Performed circumferential joints of all-metal vessels do not fail at constant and changing gas pressure.

3. *M/V* ratio of all-metal vessels depends little on vessel dimensions. This characteristic is operatively assessed by the strength of pipe steel without *M* and *V* determination.

4. Free access to the cylindrical surface of the vessel promotes simplification of maintenance and repair-reconditioning operations performance. Manufacture of all-metal vessels with application of medium diameter pipes requires simple welding equipment. Its organization does not raise any special difficulties.

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