CAPABILITIES OF APPLICATION OF HIGH-STRENGTH LOW-ALLOY PIPE STEELS FOR MANUFACTURE OF HIGH-PRESSURE VESSELS

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Technical capabilities and rationality of manufacturing mobile combined high pressure vessels of small specific weight are considered. Low-alloy low-carbon steels of higher and high strength and large diameter pipes can be used for shell billets. Butt joints acceptable in terms of properties and cyclic fatigue life are produced by multilayer submerged-arc welding, and they can be improved by arc treatment with a partial melting. Welded case is subjected to annealing without performing high-temperature strengthening and is reinforced along the cylindrical part by a composite material of a high specific strength.

Keywords: *submerged-arc welding, high-strength low-alloy steels, high-pressure vessels, welded joints, argon arc treatment, thermal cycle, structure, mechanical properties, cyclic life, specific weight*

As international experience shows the operative gas supply of such small enterprises as farms and other is reasonably to perform using mobile high pressure vessels of a small specific weight M/V, the designs and technologies of manufacture of which are developed by a number of companies. For the sea supply of liquified natural gas it is offered to manufacture of cylinders-storages of $V = 16$ m^3 ($M/V = 1.7$ t/m^3 (kg/l)) capacity and to use them at low frequency and number of loading cycles.

Reduction of specific weight and increase of cyclic life of high-pressure vessels is achieved by their reinforcement with materials of a high specific strength [1, 2]. The earlier developed technological process of manufacturing combined vessels (cylinders) of 219–360 mm diameter for using natural gas in capacity of automobile fuel includes A-TIG + TIG welding (without edge bevel) of longitudinal and circumferential welds of a shell and bottoms produced of sheet steel 30KhGSA of 3.5–6.0 mm thickness, high postweld tempering, forging of longitudinal weld, hardening and tempering to provide necessary level of strength ($\sigma_t = 950$–1000 MPa) [3]. The automobile cylinders are characterized by required serviceability under the conditions of everyday filling and using energy carrier and by small specific weight $M/V = 0.65$–0.75 kg/l. However small capacity (30–60 l) causes limitation of practical possibility of gas supply by such cylinders. For considerable increase of their capacity it is necessary to increase diameter up to 600–1000 mm and thickness of wall (using alloyed steel) up to 10–17 mm. The preparation and assembly of edges for welding becomes more complicated, the need in preheating arises, duration of welding process is 3.5–25 times increased ($v_w = 3.0$–4.5 m/h), consumption of electric power energy and argon, and formation of burnt spot on the surface of steel body during quenching in oil complicates its dressing.

In this paper the improvement of technological efficiency of manufacture of the combined high-pressure vessels of a small specific weight for operative gas supply of single consumers is considered. This can be achieved using large-diameter pipes of low-alloyed steels of higher strength and applying more efficient welding using consumable electrode.

The optimal combination of service and weight characteristics of combined welded automobile cylinders and high-pressure vessels is provided at $K = 1.60$–1.65 safety factor of welded body. To manufacture high pressure vessels the steels of different chemical composition, structure and mechanical properties and pipes of them including those welded with relation of $\sigma_{0.2}/\sigma_t$ within the limits of 0.48–0.87 are applied [4]. The increase of σ_t of steel body from 500 to 1000 MPa allows decreasing M/V of combined vessel for working pressure down to 19.6 MPa from 1.33 to 0.65 kg/l due to increase of D/S relation (diameter to wall thickness) from 31 to 63 (Figure 1). In combined vessels of steels $\sigma_t \geq 550$ MPa, $M/V \leq 1.18$–1.22 kg/l, which is lower than $M/V = 1.25$–2.0 kg/l of produced steel automobile cylinders. Keeping the relation $D/S = 0.016$–$0.032 > 0.010$ causes necessity in conductance heat treatment of the welded body, and proportional decrease of D and S results in simplification and reduction of duration of performance of welding-technological works.

Welds should have the tensile strength at the temperature of 20 °C corresponding to σ_t of base metal and KCU of not lower than 50 and 30 J/cm^2 respectively for the temperature of 20 and lower than −20 °C, and welded joints of low-alloy manganese and silicon-manganese steels should withstand tests at static bending for the angle of not lower than 80° [4]. The life of vessels of $N = 5500$ cycles can be considered as sufficient for everyday filling and consumption of gas

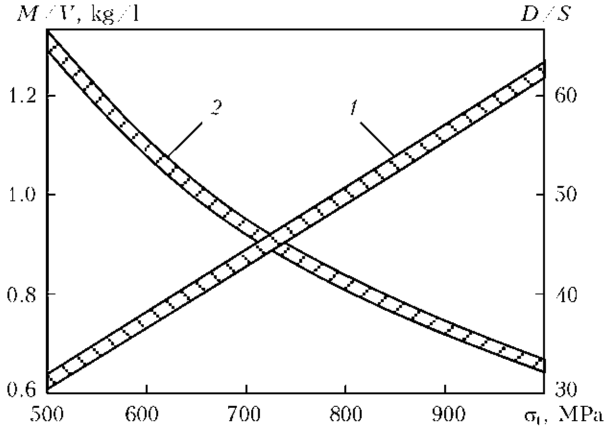

Figure 1. Influence of strength of steel on the size parameter D/S (*1*) and specific weight M/V (*2*) of combined high-pressure vessel

during 15 years of operation similar to automobile cylinders.

As is known, the high strength of low-alloy steels, including pipe steels, is provided by increase of manganese content of up to 2 %, by micro-alloying with niobium, vanadium, titanium, chromium, copper, nickel, boron, by transfer from hot rolling (normalization) to controllable rolling, thermomechanical and new kinds of treatment. Here, with decrease of content of carbon (from 0.20 to 0.03 %) and sulphur (from 0.035–0.040 to 0.010 %) and lower the considerable increase of ductility (deformability) and toughness, improvement of their weldability as compared to carbon alloyed steel is achieved [5–7]. Thus, the premises are created for rejection of heating and postweld tempering and also applying welding using consumable electrode instead of argon arc welding using non-consumable electrode. In Ukraine and abroad the pipes of large diameter are produced applying longitudinal submerged-arc welding of low-alloy pipe steels of strength class X65, X70, X80 and X100 with $\sigma_t \geq 550$, 560, 620 and 760 MPa, $\sigma_{0.2} \geq 450$, 480, 550 and 690 MPa, $\delta \geq 18$ %. The main gas pipelines welded by circumferential welds are operated under changing pressure and temperature including the conditions of the Far North. It is obvious that welded vessels manufactured of mentioned steels and pipes are acceptable for operation under less extreme conditions as well.

The analysis of data of Table 1 evidences that safety factor K of welded body of vessel can change within wide limits from 0.96 to 2.10. When K = 1.60–1.65 the specific weight of combined vessels manufactured applying steels of strength class X65, X70, X80 and X100 can be 1.08–1.11; 1.03–1.06; 0.85–0.89 and 0.76–0.77 kg/l. The prospective is the application of

Table 1. Calculation characteristics of high-pressure vessels of welded pipes for main pipelines

No.	Class of steel strength	σ_t, MPa	Pipe		Body	Vessel
			D, mm	S, mm	K	M/V, kg/l
1	X65	590	762	19.1	1.51	1.02
2		590	762	20.2	1.60	1.08
3		670	1220	18.9	1.06	0.63
4		590	914.4	25.0	1.65	1.11
5	X70	600	914.4	19.1	1.34	0.85
6		620	914.4	28.6	2.10	1.28
7		620	914.4	23.0	1.59	1.03
8*		620	914.4	24.0	1.66	1.07
9	X80	752	610	12.7	1.60	0.85
10		722	762	15.6	1.51	0.84
11		734	1016	17.5	1.29	0.70
12		750	1020	21.5	1.61	0.86
13		750	720	15.5	1.65	0.89
14		750	610	13.0	1.63	0.90
15	X100	801	1219	14.3	0.96	<0.60
16		838	1219	14.3	1.00	<0.60
17		816	914.4	13.2	1.20	0.65
18		858	914.4	13.2	1.26	0.65
19		858	914.4	17.0	1.63	0.80
20		890	914.4	15.0	1.49	0.72
21		890	914.4	16.5	1.64	0.77
22		890	1020	18.5	1.65	0.77
23		890	762	13.5	1.61	0.76
24		890	610	11.0	1.64	0.77

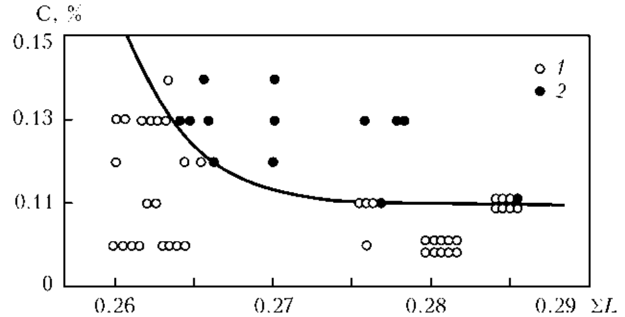

Figure 2. Influence of carbon and alloying elements on cold cracks formation in the submerged-arc welded joint of high-strength steel [9]: *1* — no cracks; *2* — cracks present

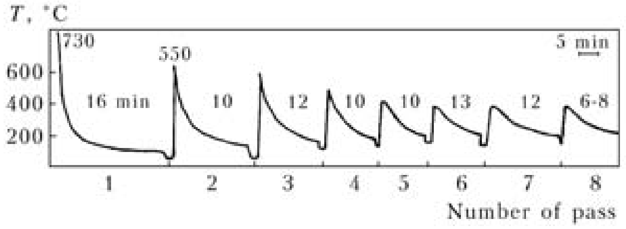

Figure 3. Characteristic thermal cycle of multilayer submerged-arc welding

pipes of steel of grade X80, the production of which is mastered in Ukraine. Therefore further our investigations were directed to the evaluation of possibility of use of tubular billets of mentioned steel as applied to manufacture of the mobile high-pressure vessels.

As the object of investigations the butt joints according to the GOST 8713–79 and 14771–76 were selected with multilayer welds of steel of grade X80 of 20 mm thickness of the following chemical composition, %: 0.094 C; 1.97 Mn; 0.362 Si; 0.03 Mo; 0.02 Nb; 0.014 Ti; 0.02 P and 0.03 S, which is characterized by the following mechanical properties: $\sigma_t = 650$ MPa, $\sigma_{0.2} = 547$ MPa, $\delta = 21.6$ %, $KCV^{+20} = 327$ J/cm^2 and $KCV^{-40} = 245.5$ J/cm^2. The carbon equivalent $C_{eq} = 0.20–0.44 < 0.45$ % calculated according to different formulae allows referring it to those not susceptible to cold cracking [8]. It corresponds also to such combination of carbon content and parameter of alloying

$$\Sigma L = (\mathrm{Mn} + \mathrm{Cr})/20 + \mathrm{Si}/30 + (\mathrm{Ni} + \mathrm{Cu})/60 + \mathrm{Mo}/15 + \mathrm{V}/10 = 0.22\ \%,$$

at which cold cracks in welded joints of high strength steels welded by submerged-arc welding are absent (Figure 2) [9]. Therefore, the submerged-arc welding of such joints is performed without preheating however preheating is recommended during welding in shielding gases and its temperature depends on carbon equivalent, thickness of steel and temperature of environment. The crack formation is prevented by autopreheating, delayed cooling, thermocycling in multipass welding.

The automatic welding of mentioned joints was erformed under flux AN-47 using wires Sv-10Kh2M and Sv-08KhM and mechanized welding in carbon dioxide was performed using wire Sv-08G2S. A part of welded joints was subjected to argon arc treatment with partial melting in the middle of a weld in the areas of transition from a weld to base metal and furnace tempering at the temperature of 600 °C during 1 h. The thermal cycles of welding (Figure 3) and argon arc treatment were recorded using thermal couple VR-20/5, fastened on the opposite side of a butt, and potentiometer KSP-4. Welded joints were investigated by metallographic, durametric methods, tested for static rupture, static bending at angle 90°, impact bending of specimens with a circular notch along the weld, fusion zone and HAZ (at the distance of 2 mm from a weld), and also for fatigue at tension with frequency of 5 Hz up to $\sigma_{max} = 300–350$ MPa of a cycle, keeping the relation $\sigma_{max}/\sigma_t = 0.48–0.56$ (the same as at cyclic tests by inner pressure of combined cylinders with welded body of steel 30KhGSA).

As was shown by analysis of thermal cycles, during deposition of the first beads of weld of joints produced both under flux, as well as in carbon dioxide at heat input of 21.6 and 9 kJ/cm^2, their cooling occurs at the speed of $w_{6/5} = 8–12$ and 14–18 °C/s which corresponds to rational interval $w_{6/5} = 5–35$ °C/s at $q/v_w = 9–35$ kJ/cm [10]. At the next passes which were performed after cooling of welded joints down to the temperatures of 90–180 and 80–120 °C (during 5–16 min), weld root is heated up to the temperatures of 680–350 and 540–290 °C. With the increase of succession and removal of beads being performed, the temperature of heating metal of the lower part of welded joints is decreased and metal is subjected to multiple short-time tempers which promote the absence of cold cracks in welded joints (Figure 4, *a*).

In the process of argon arc treatments from $v_{tr} = 7.5$ m/h ($q/v_{tr} = 12.5$ kJ/cm) and $v_{tr} = 4.8$ m/h ($q/v_{tr} = 19.5$ kJ/cm) with a partial melting of 7–10 and 13–14 mm width respectively at the places of

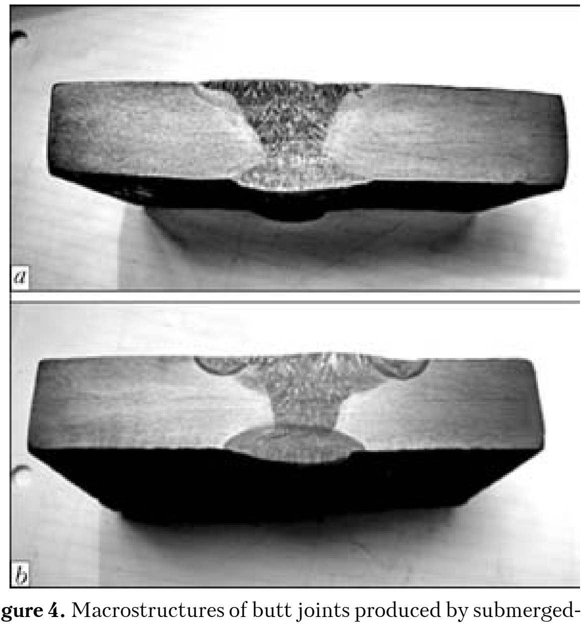

Figure 4. Macrostructures of butt joints produced by submerged-arc welding before (*a*) and after (*b*) argon arc treatment

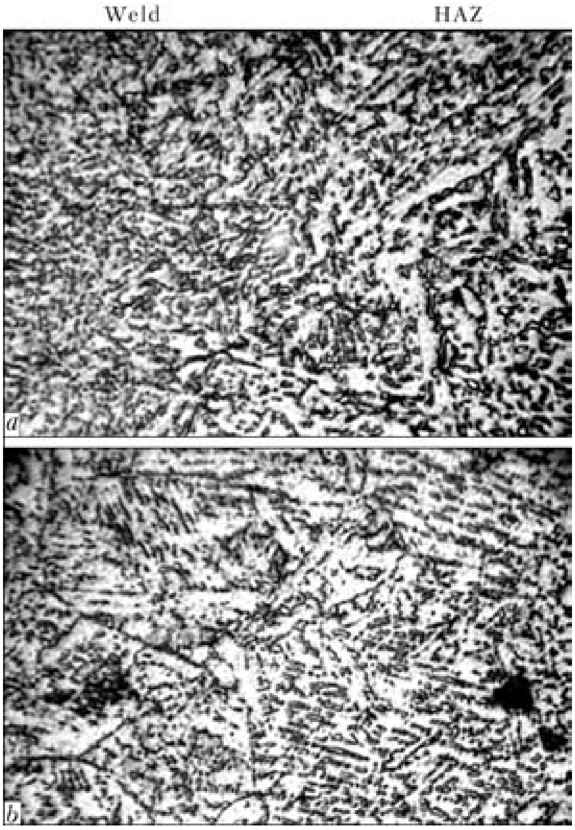

Figure 5. Microstructures (×320) of metal of fusion zone (*a*) and HAZ (*b*) of submerged-arc welded steel of grade X80

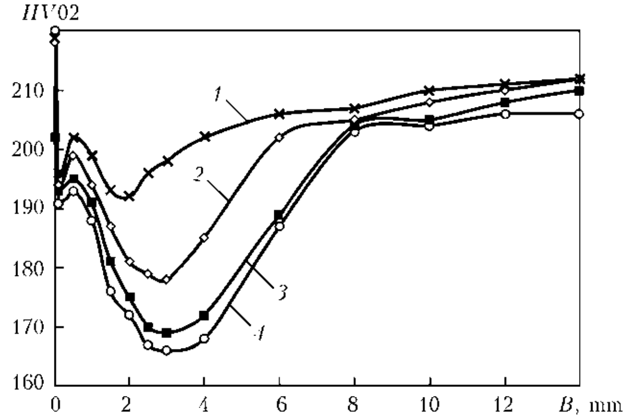

Figure 6. Distribution of hardness across the width *B* of HAZ metal on steel X80 welded under flux (*2–4*) and in carbon dioxide (*1*) in the state after welding (*1*, *2*), argon arc treatment (*3*) and high tempering (*4*)

transition of a weld to a base metal and also of 25–27 mm width at the middle of a weld the undercuts were removed, sharp transitions to a base metal (Figure 5, *b*) and indents among beads were smoothed. A welded joint is heated across the whole thickness. A metal of upper part of a joint at the depth of up to 8–12 mm undergoes phase and structural transformations. In the lower part it is exposed to short-time tempering.

As the results of metallographic investigations show, the ferrite-bainite structure with inclusions of MAC-phase is formed in HAZ metal of joints produced using submerged-arc welding (Figure 5). Its hardness is gradually decreased at the distance of 0.1–0.3 mm up to *HV*0.2–193 and at the distance of 3 mm from a weld to *HV*0.2–178 relatively to *HV*0.2–215 of a base metal (Figure 6, curve *2*). The lower weakening of HAZ metal (at the distance of 0.1–0.3 mm from a weld) up to *HV*0.2–195 and 2 mm from a weld of up to *HV*0.2–192 is observed after welding in carbon dioxide (Figure 6, curve *1*). After argon arc treatment and furnace tempering the character of distribution of hardness across the width of HAZ is not changed (Figure 6, curves *3*, *4*), and its values are decreased. The zonal reductions of hardness in HAZ metal ac-

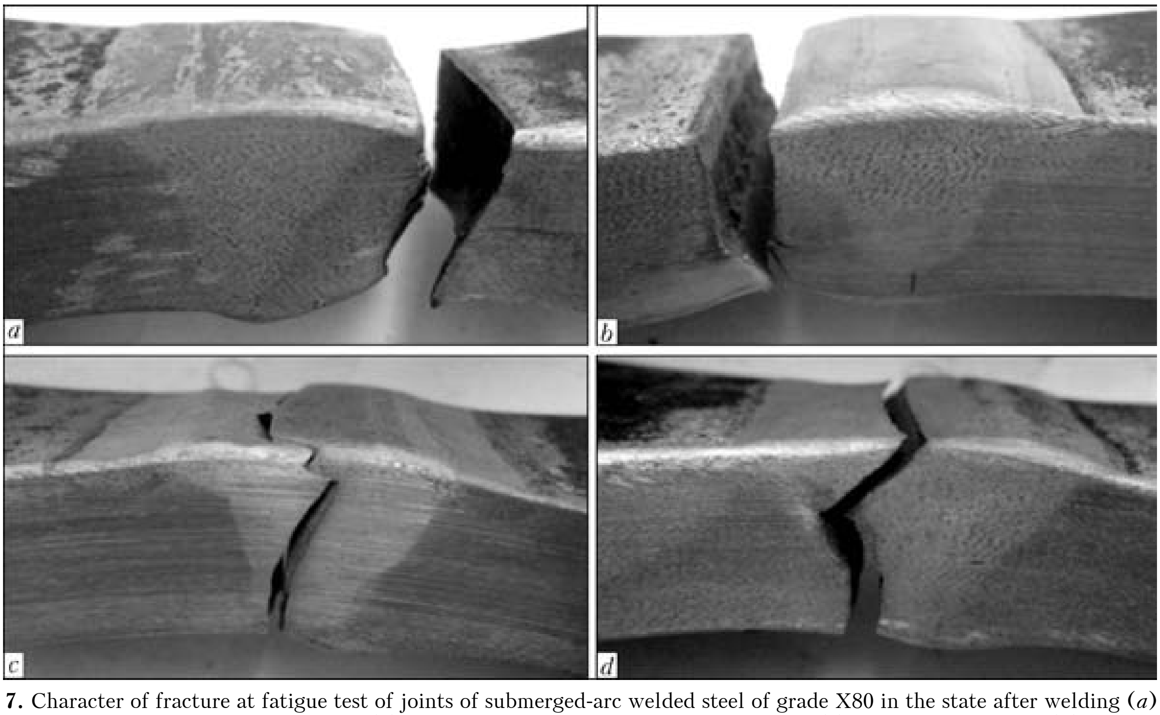

Figure 7. Character of fracture at fatigue test of joints of submerged-arc welded steel of grade X80 in the state after welding (*a*), argon arc treatment with partial melting of a weld (*b*), transition places from weld to base metal (*c*) and high tempering (*d*)

cording to our assumption is the demonstration of a localized decarburization of metal in the fusion zone and at the areas which were heated in welding up to the temperatures of transformation.

After argon arc treatments of joints with a partial melting of a weld of 10Kh2M type and transition from it to a base metal the hardness of these areas is increased up to $HV0.2$–(243–262; 230–245 and 145–163). Near the partial melts of a weld it is decreased down to $HV0.2$–(225–237) and is not almost changed on the joint reverse side. The furnace tempering causes the decrease in hardness down to $HV0.2$–(233–247). The increased hardness of chromium-molybdenum weld metal in different states proves its higher strength than that of the base metal.

The tensile strength of welded joints produced by submerged-arc welding is 610 MPa. Their fracture occurs beyond the weld. The bend angle of such joints is not lower than 90°. The impact toughness of HAZ metal is KCU^{+20} = 286 J/cm^2 and KCU^{-40} = = 144 J/cm^2 after submerged-arc welding, and KCU^{+20} = 321 J/cm^2 after welding in carbon dioxide. In weld metal of the type 10Kh2M and 08KhM produced by submerged-arc welding KCU^{+20} = 86 and 139 J/cm^2 and KCU^{-40} = 38 and 52 J/cm^2, respectively. After arc treatments and furnace tempering the impact toughness of these areas is changed negligibly (KCU^{+20} = 279–305 J/cm^2 of HAZ metal and KCU^{+20} = 87–95 J/cm^2 of weld of type 10Kh2M). As is seen, the impact toughness of welded joints of the steel of grade X80, welded under flux, exceeds standard requirements.

At fatigue test of flat specimens it was established that fracture of welded joint (Figure 7) begins from formation of cracks in the places of concentration of stresses, in particular in transitions from weld to base metal on the front or both sides, and develops along the weld, fusion zone or HAZ metal. If fracture of welded joints in postweld conditions and argon arc treatment with a partial melting in the middle of a weld begins on the front side and their life is 58,100–86,100 and 49,300–104,900 loading cycles, then the fracture is initiated at the later stage from the root part after arc partial melting of transition places from weld to base metal (the angle and radius of conjugation between weld and base metal is increased). The life of these joints is increased up to 86,300–106,400 cycles (Table 2). After high tempering, increasing the equilibrium of structure and decreasing the level of residual stresses, it is increased up to 114,100–312,400 cycles. In combination of two latter technological operations one can expect even more intensive increase of cyclic life. The established cyclic life at uniaxial tension of welded joints of low-alloyed steel in different states exceeds the life of hydraulically tested combined cylinders with a thermostrengthened body of alloyed steel (15,000–24,000 cycles [3]) 3.3–13 times.

Table 2. Cyclic life of butt joints of steel of strength class X80 produced by multilayer submerged-arc welding using wire Sv-10Kh2M

Postweld treatment	σ, MPa	N, cycle
Without treatment	300	58,100
	350	86,100
Arc partial melting of a weld	300	104,900
	350	49,300
Arc partial melting of transition places	300	106,400
	350	86,300
High tempering	300	312,400
	350	114,100

The carried out investigations prove that mobile high pressure vessels for operative supply of liquified gases are reasonable to be manufactured using pipes of large diameter in capacity of billets of shells and sheet rolled metal to form bottoms of low-alloyed steels of increased strength with a low carbon content. Circumferential welds of shells and bottoms of wall thickness of 13–24 mm are reasonable to be made using multilayer submerged-arc butt welding without preheating. Proportional decrease of wall thickness and diameter of vessel promotes simplification and decrease of duration of welding-technological works. To improve serviceability it is reasonable to subject butt joints to arc treatment with a partial melting of transition places from weld to base metal. The welded body is subjected to an obligatory tempering. Its cylindrical part is strengthened by polymer composite material of a high specific strength.

Here, the formation and welding of shell, forging of longitudinal weld, furnace postweld tempering and high-temperature heating with further hardening are eliminated.

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