TECHNOLOGY AND EQUIPMENT FOR MANUFACTURE OF HIGH-PRESSURE CYLINDER BODIES OF SHEET ROLLED STEEL

M.M. SAVITSKY, A.S. PISMENNY, E.M. SAVITSKAYA, S.I. PRITULA and **S.K. BABENKO**
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

At the E.O. Paton Electric Welding Institute the design and technology have been developed for manufacture of combined high-pressure cylinders with a mass-dimensional factor $M/V \le 0.65$ kg/l for use in motor-vehicle transport. The cylinder consists of a pressurized body and a strengthening composite sheath. To manufacture the cylinder body, welded of thin-sheet steel, a specialized assembly-welding equipment and technology of precision welding, subsequent inspection and heat treatment of welded joints were developed. Production lines of up to 20,000 and 100,000 cylinders per year with their safety factor above 2.6 were created.

Keywords: *arc welding, motor-vehicle cylinders, high pressure, life of equipment, technology of welding, longitudinally- and spirally-welded shells, production lines*

The natural gas, namely methane, is one of the most widely-spread and promising energy carriers on the Earth. Its explored reserves approach 10^{12} and predicted ones (taking into account hydrates) approach 10^{15}–10^{16} nm^3 [1]. Production of gas and its preparation for use are economically and ecologically less expensive as compared with oil, and combustion stipulates the lower (1.5–2.5 times) content of oxides of carbon and nitrogen, as well as aromatic hydrocarbons in combustion products [2]. Moreover, the gas cost is approximately 2 times lower than the cost of benzene, and its application as a motor fuel does not require the change in design of motors and does not exclude the feasibility of their service using gas, benzene or their mixtures [3]. In addition, there are some inconveniences in arrangement of additional charge capacities (high-pressure vessels) on the board of motor vehicle. In this connection, some companies modified the designs of bodies and started the manufacture of motor cars with built-in cylinders.

Requirements for cylinders are rather high [4] and a definite level of technological discipline and mechanization of works is necessary for their production. This is a premise for organizing the highly-technological manufacturing, and the modern rates of motorization of the world and consumption of oil resources allow predicting the challenges for these kinds of manufacturing. Moreover, about 900 mln of registered transport vehicles exhaust up to 60 % of all pollutions into environment. Therefore, at the present stage the application of gas as a motor fuel will make it possible to decrease the pollution of environment and to delay the collapse of automotive industry because of exhaustion of oil reserves, and also to develop the more acceptable solutions, for example, producing fuel, including gas, from recovered sources, hybrid motor vehicles, such as «gas–electric energy» and so on.

The problem of gasifying the motor vehicle transport was considered as far back as last century, but these were mainly the pioneering projects which allowed gaining the experience and preparing the base for transition to the wide-scale solutions.

At present, about 9 mln motor vehicles are in service using the natural gas, where a compressed gas is mainly used, as the existing cryogenic tanks for liquefied methane do not guarantee its long-term storage on the board, and most motor vehicles are used at sufficiently large intervals, i.e. there is no alternative to high-pressure cylinders.

At the present stage the steel cylinders, manufactured of all-drawn pipe billet by a hot rolling of edges, found a wide spreading [5]. This technology was tested earlier on cylinders for technical gases and attracted manufacturers by its accessibility and simplicity. However, it was not managed to organize the mass production of these cylinders in Ukraine, because of difficulty in producing the tubular billet without laminations and with small tolerances for wall thickness. Moreover, the formation of bottoms by rolling can be realized only at a definite ratio of diameter to pipe wall thickness. This limits the possibility of manufacture of cylinders of different types and sizes with a stable mass-dimensional characteristic (mass-to-volume ratio M/V) of not more than 1 kg/l.

The further decrease and stabilization of this characteristic was realized in design of metal-plastic cylinder with a welded body of sheet steel, suggested by the E.O. Paton Electric Welding Institute and S.P. Timoshenko Institute of Mechanics [6]. The body consists of a longitudinally-welded shell and two stamped semi-elliptic bottoms, welded to it by circumferential welds, a neck is welded-in into one of these bottoms. As the body is manufactured of low-strength low-alloy steels (shell of steel 09G2SF of 3 mm thickness, and bottom — of steel 09G2S 6 mm thick), it is strengthened by a load-carrying fiber-glass sheath of a «cocoon» type, made by a scheme of a longitudinal-transverse winding. The cylinder has a stable mass-dimensional characteristic $M/V \approx 0.9$ kg/l, safety factor is not less than 2.6 and withstands up to 40,000 charges.

From the point of view of owners of motor car transport the cylinders of this design have the excessive mass, and from the point of view of manufacturers they require increased expenses for formation of a composite sheath. The further improvement of design was realized using high-strength steels [7]. Here, the semi-spherical bottoms were used, in which the operating stresses are 2 times lower than in a cylindrical part of the body, thus refusing their additional strengthening, and providing the equal strength of all elements of structure by a circular winding of a cylindrical part of the cylinder [8, 9]. This simplified radically the technology and equipment for the sheath formation.

The required safety factor of new cylinders is determined mainly by mechanical properties of steel, which are preset by an initial structure and conditions of metal heat treatment [10]. At static and dynamic loading by internal pressure the problem of equal strength of welded joints was solved for different levels of strength up to 2000 MPa [11]. However, at a low-cycle loading the feasibility of application of this solution was not confirmed [12]. Here, the negative role was played by the imperfection of the joint geometric sizes. As is known, it is very difficult to provide the perfect assembly of edges being welded in assembly of thin-walled elements of the body due to ovality of parts after rolling and stamping. This results in violation of a smooth transition from the weld to the parent metal and probability of formation of high local concentration of stresses is increased, thus leading to the development of microplastic deformation and premature exhaustion of safety factor of metal in confined areas.

The attained amount of cycles of loading (ST SEV 3648–82) $[N]$ is determined by the expression

$$[N] = \frac{1}{n_N}\left[\frac{A}{\left(\sigma_A - \dfrac{B}{n_\sigma}\right)}\left(\frac{2300 - t}{2300}\right)\right]^2,$$

where n_N is the safety factor by the number of cycles; A, B are the characteristics of material; σ_A is the amplitude of stresses; n_σ is the safety factor by stresses; t is the temperature.

The life of welded joints depends greatly on such geometric parameters, as displacement of edges (Figure 1, *a*) and radius of weld conjugation with parent metal (Figure 1, *b*). This dependence is higher at a lower ductility (elongation δ) of metal. The obtained calculation data are well correlated with results of hydraulic tests of real cylinders (light signs), in which the values of edge displacements and radii of conjugation were determined after depressurization of cylinders in places of fatigue cracks initiation.

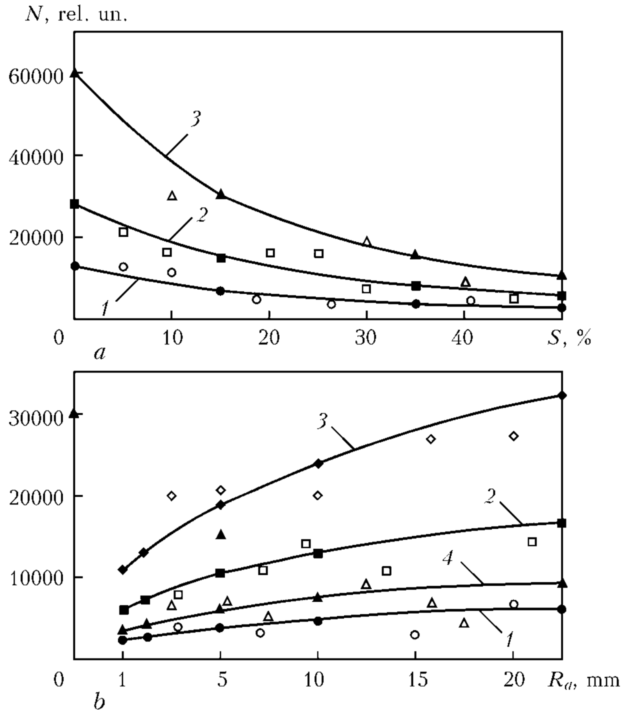

Figure 1. Dependence of cylinder life on geometric parameters of welded joint: displacement of edges (*a*) and radius of weld conjugation with parent metal (*b*) at different levels of metal elongation: *1* — δ = 8; *2* — 12; *3* — 18; *4* — 10 %; light signs — real cylinders

To eliminate the diplanation of edges in serial manufacturing of cylinders, the assembly-welding equipment has been developed which allows parts during assembly to be deformed elastically, eliminating the ovality and forming the welded joints with minimum (δ ≥ 10 %) displacement of edges (Figure 2). Welding in this equipment is performed on one side per one or two passes (Figure 3, *a*). During the first pass, which is performed with a complete penetration of edges, a load-carrying weld is formed, which is in compliance with chemical composition of the parent metal. During the second pass, the optimum width and weld reinforcement height are provided and, consequently, a necessary radius of its conjugation with the parent metal. For this purpose, the welding of the first pass is made in argon using a special activating flux, which increases the arc penetrability at lowered currents and provides penetration of up to 10 mm thick steel for one pass without edge preparation. This allows preventing the formation of coarse hardening structures in weld and HAZ metal, as well as defects of types of pores, lacks of penetration, lacks of fusion, cracks, and forming the load-carrying welds of I, II classes according to GOST 23055–78 during the first pass, which have chemical composition similar to the parent metal. The second pass is made using a filler wire and can be used for improvement of geometry, structure and ductility of the weld metal. The conformity of weld to the required class of quality is evaluated by 100 % X-ray method.

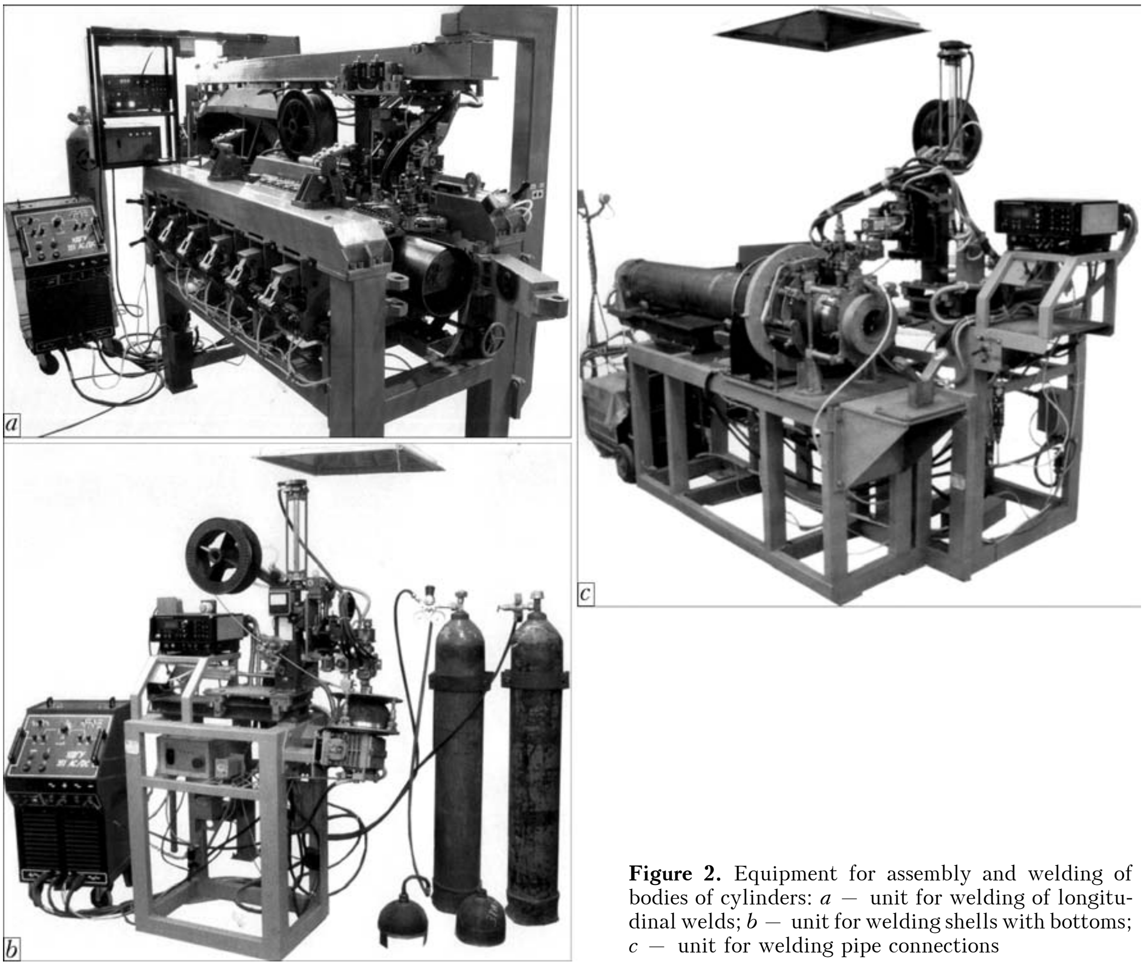

Figure 2. Equipment for assembly and welding of bodies of cylinders: *a* — unit for welding of longitudinal welds; *b* — unit for welding shells with bottoms; *c* — unit for welding pipe connections

The comparative tests carried out by one of the foreign companies showed that the micro-alloy steel joints, made by the above-described technology, are superior to joints, welded by plasma, electron beam, laser, consumable electrode in gas mixtures and non-consumable electrode in argon. They have the higher resistance against the formation of fatigue cracks at a low-cycle loading. As to the medium-carbon steels, hardened with the formation of martensite, so it occurred in a number of factors, defining the resistance against the fracture of high-strength steel butt joints, that initial structure of metal of weld and HAZ is important here, or rather the fact how this structure can be transformed and approach the structure of the parent metal after final treatment. It was found that if, after postweld treatment of joints of steels of 25SNMVFA or 30KhGSA type, to transform the bainite-martensite structure of weld and HAZ metal, hardened from welding heading, into a relatively equilibrium structure of temper sorbite (Figure 4), then the texture of cast weld metal is disappeared after hardening and austenite grain is refined in the area of HAZ metal overheating. As a result of leveling the differences of structures of parent metal and joint, the service life of cylinders is increased from 1600–1800 up to 25,000–30,000 charges.

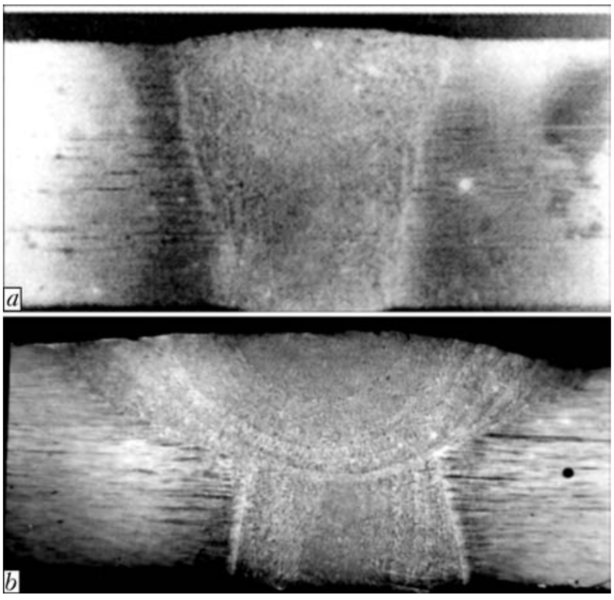

Figure 3. Macrosections of single- (*a*) and two-layer (*b*) welds

The NDT of welded joints is rather important operation in the technological process. The organizing of control using X-ray method requires working places, protected from radiation, financial and temporary expenses, that leads under the conditions of a serial production to the formation of weak points in the production line. A challenging addition to the X-ray inspection in a serial production of high-pressure cylinders is the new method: a shear speckle-interferometry, or shearography [13, 14]. It allows obtain-

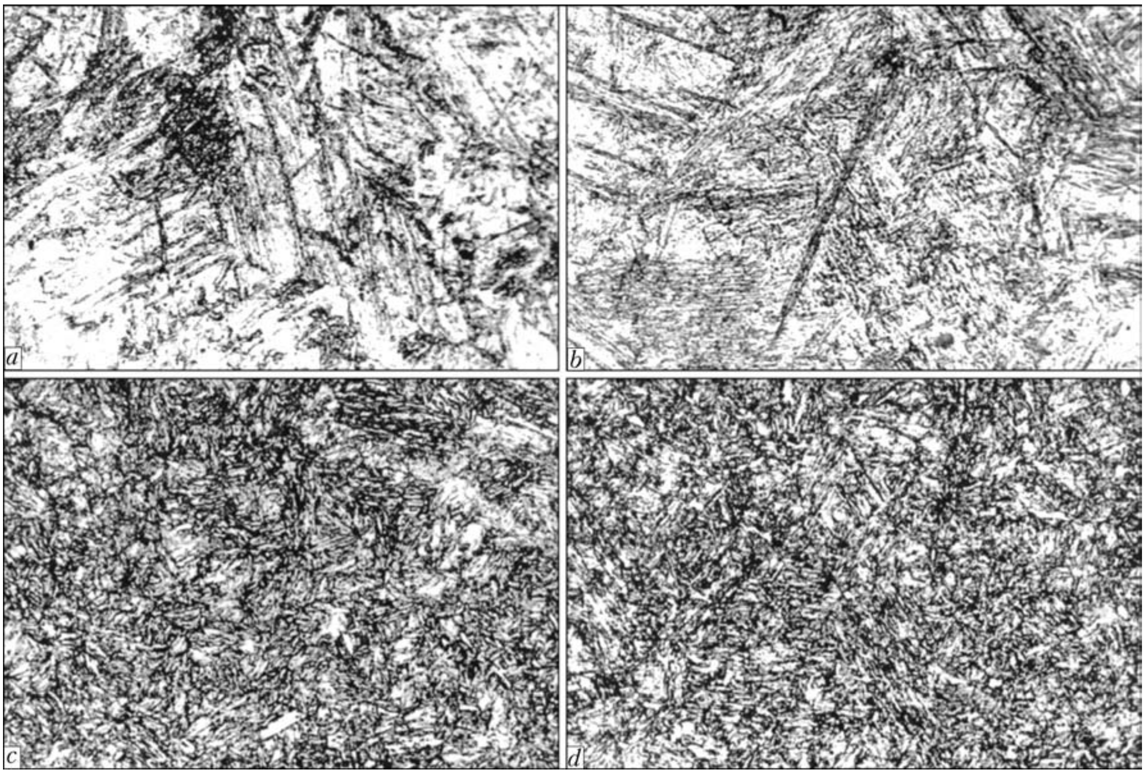

Figure 4. Microstructures (×300) of metal of weld and HAZ after welding (*a, b*) and local heat treatment (*c, d*)

ing the in-process complete information about technical condition of object being examined and revealing the potentially defect-hazardous places, which then can be selectively controlled by the X-ray method.

The main principle of the shearography is as follows. The cylinder area being examined is subjected to loading by the internal pressure or external heating and then illuminated by a coherent laser beam. The reflected light flow in the interferometer is divided with a shear into two wave fronts, converted into an electric signal and transferred to computer for the processing. The results are recorded on electron carriers and can serve as a target indication for next identification of defect using standard X-ray methods. Evidently, this method can be also applied for evaluation of cylinders condition at their periodic inspection. Speckle-patterns, recorded during initial inspection, can be compared with patterns, obtained after a definite period of service and, thus, to determine the service life of cylinders.

As the investigations showed [14], it is possible to reveal at elasto-deformed state of the object not only defects, recorded in X-ray inspection, but also local concentrations of stresses, usually not-shown on radiograms, but influencing the life and reliability of the cylinders.

Basing on the developed designs of combined cylinders, complex of technologies and a non-standard equipment, a production line of assembly, welding, inspection and heat treatment of cylinder bodies of sheet steel (Figure 5, *a*) and also formation of a composite sheath has been created. The line of this type allows organizing the updated production of combined cylinders with a longitudinally-welded shell of efficiency up to 24,000 cylinders per a year. The mass-dimensional characteristic of these cylinders is about 0.65 kg/l. The production cost of cylinders is 2 and more times lower than the cost of similar cylinders of foreign production.

The drawbacks of a longitudinally-welded shell are usually the probability of location of physical and geometric imperfections of a longitudinal weld along the generatrix, and also non-balancing of rigidity and residual stresses in spite of the fact that the level of operating stresses from radial forces in shell is 2 times higher than those from axial forces. To eliminate these drawbacks, the technology envisages the preliminary bending of edges, mechanical-heat treatment of joints and subsequent calibration of the shell. As a whole, this allowed providing the equal strength of all the areas of the shell and increasing the uniformity of distribution of operating stresses in them, however, leading to the increase in amount of technological operations.

A spirally-welded shell is subjected to the influence of the above-mentioned factors to a less degree, as the vectors of radial stresses are not normal to the weld plane, and the zones of an increased rigidity and elasto-plastic deformations are not concentrated in one plane [15] that eliminates the required calibrations. Besides, the combination of operation of formation and welding of butt in a single mechanism allows eliminating the bending of edges and intermediate transporting operation.

To shorten further the cycle of manufacturing, to reduce the cost and to increase the rates of manufacture

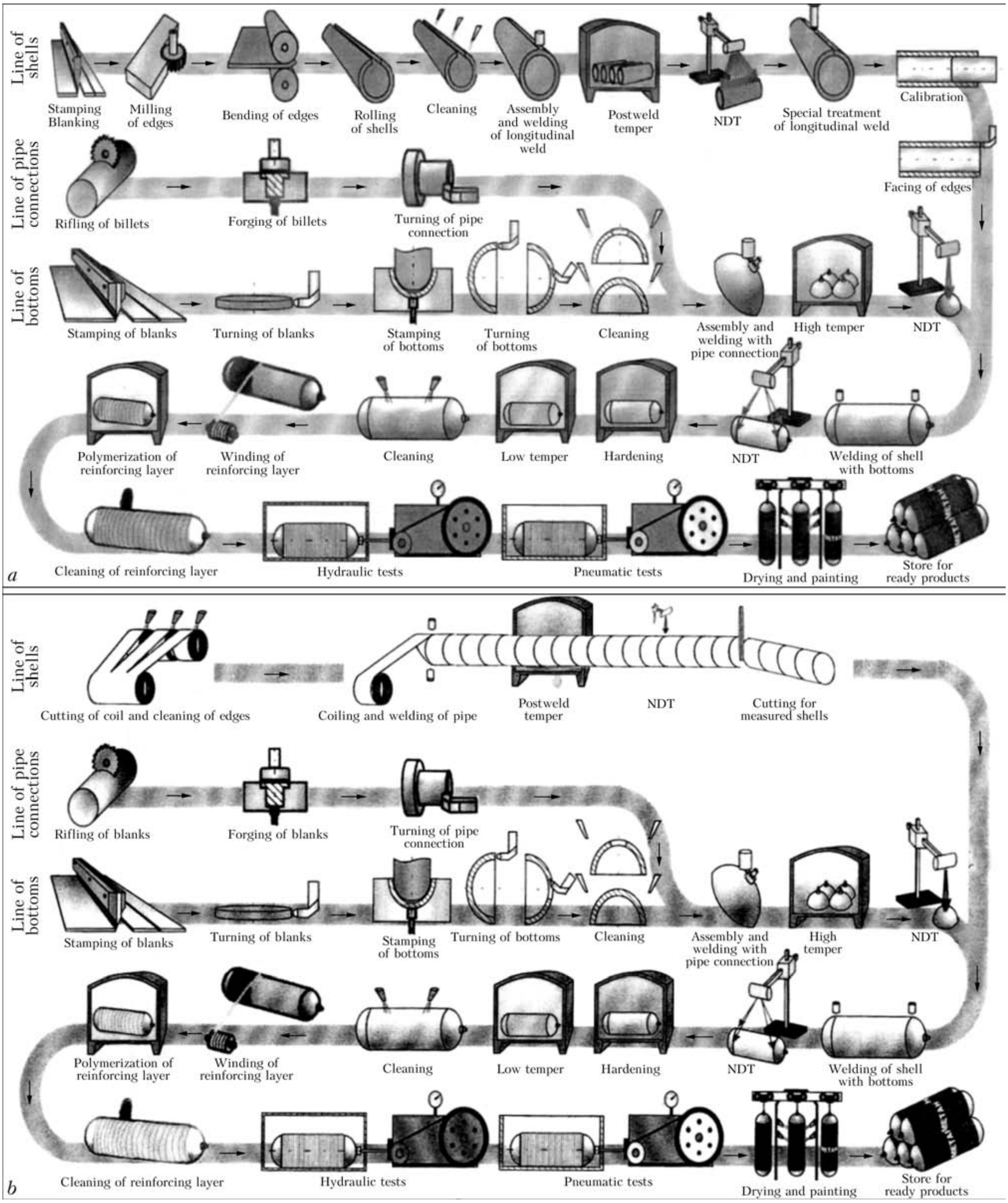

Figure 5. Technological line of manufacture of cylinders with longitudinally- (*a*) and spirally-welded (*b*) shells

of cylinders, the production line of the second type is also offered (Figure 5, *b*), the distinguished feature of which is the possibility of application of high-efficient method of high-frequency welding [16].

Equipment has been designed and passed trials in welding of special-purpose pipes. The equipment arrangement into the line of cylinders production makes it possible to combine up to five technological operations in one unit, including formation, welding and heat treatment of tubular billet and to refuse three more operations as being not required. As a heat source, the welding arc can also be used at a some decrease in speed of tubular billet manufacture. This will allow balancing the load of all the elements of the line under the conditions of small-serial production or instable demand for products. Under the conditions

Diameter of pipes being welded depending on thickness and width of billet strip

Pipe diameter, mm	Wall thickness, mm	Strip width, mm
75–100	0.5–1.5 (2.5)*	100
100–200	0.8–2.0 (3.0)	100
200–250	0.8–2.5 (3.5)	200
300–700	1.0–3.0 (4.5)	200, 300, 500 (depends on unit type)

*At 260 kW power of generator of high-frequency current.

of a large-serial or mass production, it is rational to apply the high-frequency welding, the main characteristics of which are given in the Table.

At present the industrial technology has been developed and designing documentation has been worked out for the equipment for welding of spirally-welded pipes of diameter from 75 up to 700 mm under the shop conditions. Mock-ups of bodies of different-purpose cylinders, manufactured of these pipes and tested, gave a positive result. The appearance of the mock-up of the cylinder body after tests using internal pressure is presented in Figure 6.

The main technical characteristics of equipment in the condition of high-frequency welding are as follows:

Welding speed, m/min	30–40
Speed of pipe output, m/min	8–12
Efficiency, kilometer of pipes per shift	1.0–1.5
Power of generator of high-frequency current, kW	160–250
Capacity of electric drives, kW	8
Length of pipes, m	any
Voltage of electric equipment supply (50 Hz), V	380
Materials to be welded	steel, aluminium
Area occupied by welding line, m^2	150–200

It should be noted in conclusion that the design, technologies of welding and heat treatment, as well as non-standard assembly-welding equipment developed at the E.O. Paton Electric Welding Institute, make it possible to manufacture combined welded cylinders with a stable mass-dimensional characteristic $M/V = 0.65$ kg/l and service life of more than 15,000 charges. According to TU 28.2-05416923-072:2005 a series of cylinders was manufactured with a safety factor (ratio of pressure of depressurization $P_{\rm depr}$ to operating pressure $P_{\rm op}$) equal to more than 2.6, which is preserved stable after 15,000 charges.

To organize the serial production of cylinders with a longitudinally-welded shell, the production line of the first type can be used. When necessary to provide the mass production of cylinders, it is rational to use the line of the second type, based on manufacture of a spirally-welded shell.

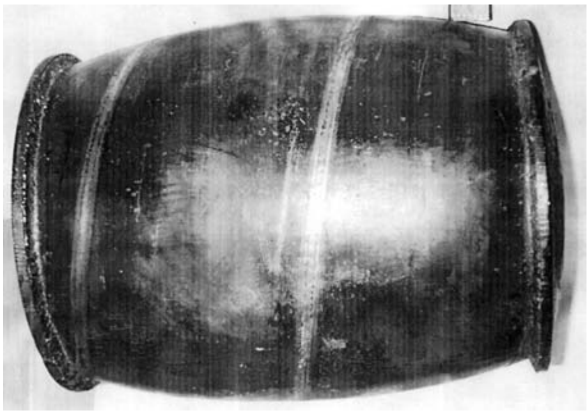

Figure 6. Appearance of mock-up of body of spirally-welded cylinder after tests using internal pressure

1. Karp, I.M., Eger, D.O., Zarubin, Yu.O. et al. (2006) *State-of-the-art and prospects of development of oil and gas complex*. Kyiv: Naukova Dumka.
2. Matsuyama, K. (2007) Trend of automobile vehicles and the joining technologies. *Riv. Ital. Saldatura*, **5**, 683–693.
3. Volkov, V., Kaplun, S.V., Zerya, A.V. (2007) New step in application of compressed natural gas as a motor fuel. *Avtozaprav. Kompleks + Alternat. Toplivo*, **6**, 57–58.
4. (2001) *Agreement on principles of technical regulations uniformity for complex vehicles, equipment objects and parts being mounted and/or used on wheel vehicles and on conditions of potential recognition of official statements issued on the base of these regulations*: UNO, E/ECE/TRANS/505. Rev. 2/Add tog 12 June 2001.
5. Sakhatov, R.M. (2009) Shatterproof metal-composite cylinders BMK-300V and others. *Avtozaprav. Kompleks + Alternat. Toplivo*, **4**, 51–54.
6. Polevoj, V.A., Ozerov, V.I., Savichenko, A.A. et al. (1992) Sructure and technology of production of metal-plastic cylinders. *Gazovaya Promyshlennost*, **11**, 30–31.
7. Paton, B.E., Savitsky, M.M., Kuzmenko, G.V. (1994) Prospects of application of high-strength medium-alloy steels in high-pressure motor transport welded cylinders. *Avtomatich. Svarka*, **3**, 4–9.
8. Savitsky, M.M., Kulik, V.M., Lupan, A.P. et al. *Combined cylinder*. Pat. 44793 Ukraine. Publ. 15.03.2002.
9. Savitsky, M.M., Kulik, V.M., Savichenko, O.O. et al. *Cylinder*. Pat. 82000 Ukraine. Publ. 25.02.2008.
10. Pokrovskaya, N.G., Petrakov, A.F., Shalkevich, A.B. (2000) Current high-strength steels for aircraft engineering products. *Metallovedenie i Term. Obrab. Metallov*, 3(**2**), 23–26.
11. Savitsky, M.M. (1991) Weldability of high purity alloy steels. In: *Proc. of Int. Seminar on Metallurgical Requirements of Producers and Consumers to Weldability of Welding Products*. Kiev, 10–15.
12. Kurkin, S.A. (1976) *Strength of pressurized welded thin-wall vessels*. Moscow: Mashinostroenie.
13. Lobanov, L.M., Pivtorak, V.A., Olejnik, E.M. et al. (2003) Electron shearography as a new method for diagnostics of materials and structures. *V Mire Nerazrush. Kontrolya*, **4**, 67–69.
14. Olijnyk, O.M. (2004) *Nondestructive testing of machine-building structures by electron shearography method*: Syn. of Thesis for Cand. of Techn. Sci. Degree. Iv.-Frankivsk: NTU Nafty i Gazy.
15. Pismenny, A.S., Polukhin, V.V., Polukhin, Vl.V. et al. (2005) Production and application of thin-walled spiral-welded pipes. *The Paton Welding J.*, **9**, 29–32.
16. Pismenny, A.S. (2008) *High-strength steel of metal products*. Ed. by B.E. Paton. Kiev: PWI.