FLASH-BUTT WELDING OF THICK-WALLED PIPES FROM HIGH-STRENGTH STEELS OF K56 STRENGTH CLASS

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Technology was developed for flash-butt welding of 1219 mm diameter pipes with 27 mm wall thickness from 10G2FB steel of strength class K56, designed for construction of off-shore gas pipelines. Admissible limits of variation of the main welding parameters ensuring the required quality of welded joints were determined. Required level of mechanical properties of the joints is achieved by local postweld high-temperature heat treatment in combination with accelerated cooling.

Keywords: *flash-butt welding, pipelines, high-strength steel, normative requirements, weldability, welding mode, welding mode parameters, welding process programming, flashing process, set power, mechanical testing, reject indications, heat-affected zone, joint quality, heat treatment, microstructure, grain, ultimate tensile, strength, impact toughness*

In 1980–1990s flash-butt welding (FBW) was widely used for joining position butts of pipes in construction of various pipelines with up to 20 mm wall thickness from steels of K52–K54 strength class.

Technology and equipment for FBW performance were developed at the E.O. Paton Electric Welding Institute together with Pskov Plant of Heavy Electric Welding Equipment (PPHEWE) with the participation of organizations of USSR Minneftegazstroj. Starting from 1980, PPHEWE mastered industrial production of equipment complexes «Sever-1», which include in-pipe welding machine USO 400 (K700) with internal flash-remover, external flash-remover, device for cleaning pipe inner surface to accommodate contact shoes and mobile electric power plant of 1000 kV·A power. «Sever-1» complexes were used to weld more than 6000 km of 1420 mm diameter pipelines (predominantly in Extreme North regions). Here high productivity of FBW process was achieved at minimum labour consumption [1]. Experience accumulated over many years of FBW application is indicative of stable high quality of welded joints that is practically independent of weather conditions or operator qualifications.

Over the last decade, intensive construction of super high-capacity pipelines operating at increased pressure (12–150 MPa) is observed. They are constructed of pipes from high-strength steels of K56–K65 strength class with wall thickness of 27–36 mm and more. Higher requirements are made of the quality of such pipe joints that is specified in modern normative documents.

As labour consumption of operations on welding position butts of thick-walled pipes in pipeline construction is considerably increased, application of high-efficient FBW process is highly promising.

Equipment available for performance of FBW, as well as «Styk» complexes for flux-cored wire arc welding, which were widely applied in the USSR, cannot be used to solve the above task, because of their technical capabilities. In addition, higher requirements are now made of mechanical property values of welded joints compared to normatives of 1980–1990s.

In this connection in recent years the E.O. Paton Electric Welding Institute and «Pskovelektrosvar» plant (RF) performed integrated development of new generation technology and equipment for FBW of thick-walled pipes. Under this project, weldability of thick-walled pipes from 10G2FB steel of strength class K56 was studied. These steels are applied in construction of off-shore pipelines. The objective of these investigations was development of the technology of welding pipes from the above-mentioned steel with 27 mm wall thickness that ensures improvement of mechanical properties of the joints, in keeping with current standards [2, 3].

Selection of the scope of investigations was determined by customer requirements to the first samples of developed equipment for the purpose of its application at construction of off-shore pipelines.

Development of welding technology was performed on large-size samples-sectors with welded cross-section of 8640 mm^2. Sectors of width B = = 320 mm were cut out of pipes with wall thickness δ = 27 mm, made from sheet steel 10G2FB produced by controlled rolling with accelerated cooling. Pipe metal had the following composition, wt.%: 0.06 C; 0.21 Si; 1.42 Mn; 0.12 Ni; 0.07 Mo; 0.04 V; 0.04 Al; 0.02 Ti; 0.05 Cr; 0.02 Nb; 0.004 S; 0.012 P.

Mechanical properties of pipe metal were as follows:

$$\sigma_t = 546.7\text{–}556.8\ \text{MPa};\ \sigma_y = 484.4\text{–}493.5\ \text{MPa};$$
$$KCV_{+20} = 334.7\text{–}336.6\ \text{J/cm}^2;$$
$$KCV_{-40} = 333.0\text{–}336.6\ \text{J/cm}^2.$$

Mechanical testing of welded butt joints was performed at the E.O. Paton Electric Welding Institute and Strength Laboratory of TsNIITMASh in keeping with the normative requirements [2, 3]. Metallographic investigations were conducted in light microscope «Neophot-32» in the Laboratory of Metallographic Investigations. The above laboratories are certified in keeping with the international standards.

FBW technology is based on the process of continuous flash-butt welding with programmed variation of the main parameters of the mode which was verified with positive result in welding by «Sever-1» complexes that allowed elimination to a considerable extent of the influence of accuracy of pipe fit up before welding on welded joint formation.

Welding mode is determined by selection of the program of variation of the main parameters of FBW process. Program (Figure 1) envisages four periods of the welding process [4].

In period *I* a stable flashing process is excited. In period *II* heating of the ends of pipes being welded up to the specified temperature is performed. In period *III* the flashing process is intensified to ensure optimum conditions for joint formation in the spark gap. In period *IV* deformation of heated ends and joint formation take place.

In addition to the main parameter values (v_{fl} — pipe feed rate in periods of excitation of the process of ends flashing and heating; $U_{2o.c}$ — welding transformer open-circuit voltage; t_w — welding time; P_{up} — upset force; v_{up} — upsetting speed), preset by the program, for each of the above flashing periods it is necessary to determine the algorithm of control of feedbacks between individual parameters at selection of the optimum welding mode.

The objective of these studies was selection of optimum welding modes providing the required mechanical properties of welded joints, as well as the possibility of producing sound welded joints at minimum values of consumed power and metal losses for flashing.

Welding of sectors cut out of pipes was performed in upgraded K1000 machine. The taken ratio of sector width, welded section area ($B\times\delta$) and resistance of this machine welding circuit, allowed a sufficiently accurate simulation of the process of flashing of a full-scale pipe of 1219 mm diameter, its power values

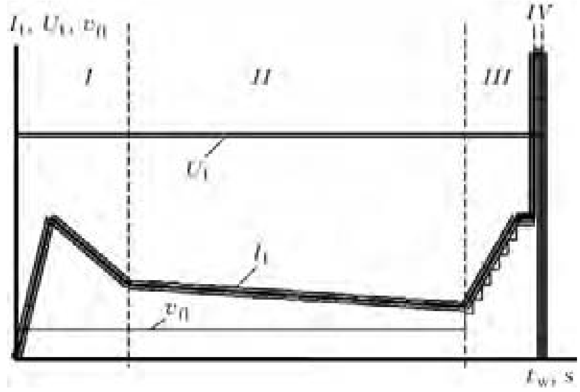

Figure 1. Program of variation of the main parameters of the mode of FBW of pipes: I_1, U_1 — primary welding current and voltage, respectively; *I–IV* — programming periods

and determination of the main parameters of the developed machine for FBW of such pipes.

As follows from the above, at the first stage conditions are created for excitation of a stable flashing process, in which the angle of edges bevel (chamfer) α at pipe ends has an essential role. In this connection, studies of the influence of the angle of edge preparation of pipe ends on power required for excitation of the flashing process were conducted.

Sample ends in the welding area were cut by gas cutting, and edge preparation angle was changed from 0 up to 45° (Figure 2). Power required for excitation of stable flashing decreases with α increase (Figure 3) [5]. At $\alpha > 15°$ the consumed power during excitation of the flashing process (period *I*) and achievement of stable flashing (period *II*) remains constant. It is rational to assume the same loading of the power source at the initial and final periods of welding, then the optimum groove angle is equal to $\alpha = 15°$. In sample welding groove angle was taken to be $\alpha = 15°$.

At determination of optimum duration of stable flashing (period *II*), in order to obtain sound joints it is necessary to ensure heating zone larger than in welding of parts 15–20 mm thick. Maximum possible heating at continuous flashing is limited by achieving such a quasi-equilibrium thermal state, at which extension of flashing duration is not accompanied by heat increment in the ends of parts being heated. In samples of used dimensions such a state is reached in the case of increase of flashing duration up to 200 s

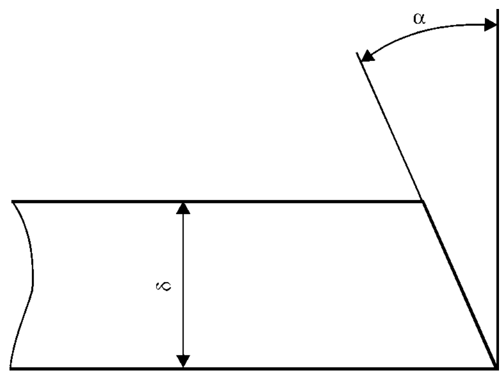

Figure 2. Edge preparation on sample ends

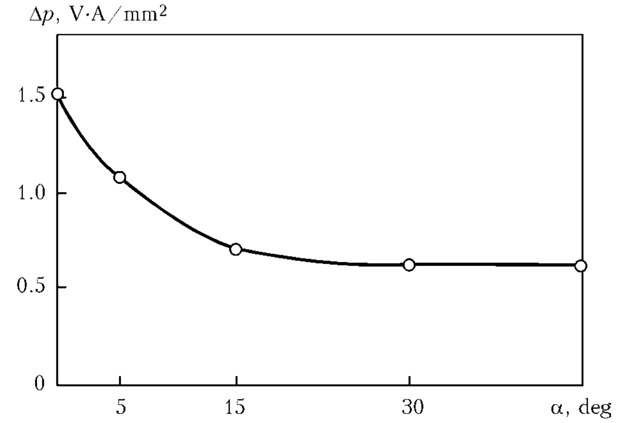

Figure 3. Dependence of specific power Δp on groove angle α of edges [5]

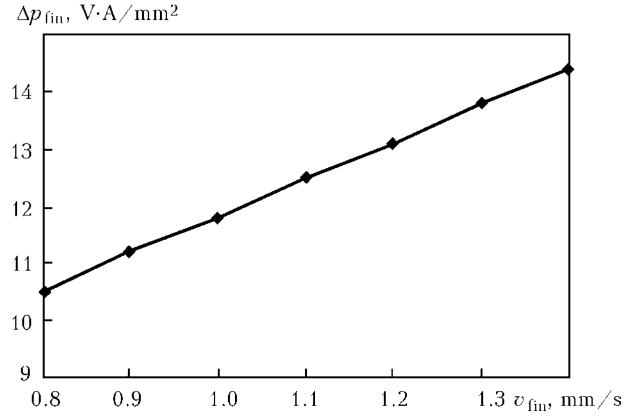

Figure 5. Dependence of specific consumed power Δp_{fin} on final flashing speed v_{fin}

at optimum speed $v_{fl} = 0.2$ mm/s [6]. As such a «soft» heating mode corresponds to minimum consumed power, the above parameters are taken as the optimum ones at determination of the program for basic mode of welding sample batches in period *II*. Duration of period *III* and program of increase of displacement speed up to final speed v_{fin} were taken allowing for the results of earlier research [6]. Figure 4 gives a record of oscillograms of the main welding parameters with the used «soft» mode.

Specific consumed power during stable flashing is equal to $\Delta p_{fl} = 6.1$ V·A/mm^2, and in the final period of flashing before upsetting it is increased up to $\Delta p_{fin} =$ $= 13$ V·A/mm^2 for 2–3 s. At the same program of variation of speed v_{fin}, values of consumed power rise in proportion to increase of v_{fin} in the range of 0.8–1.4 mm/s. Figure 5 gives dependence $\Delta p_{fin} = f(v_{fin})$ at voltage $U_{2o.c} = 6.8$ V. Value of Δp_{fin} determines set power of power source [7]. In welding pipes of the above cross-section a power source with set power of 1320 kV·A will be required. But as the modern mobile power stations allow short-time overloading of up to 10–15 %, the power can be even lower.

The above data show that determination of optimum v_{fin} value has an essential influence on power source selection and technico-economic indices. In this connection, the influence of v_{fin} values on welded joint quality was studied. For this purpose four batches of butt joints were welded in the «soft» mode with final speed $v_{fin} = 0.9$, 1.0, 1.1 and 1.2 mm/s. Each batch consisted of five butt joints: three were used for evaluation of mechanical properties, and two were broken in the joint plane. Samples were tested for rupture and bending in keeping with the standards [2, 3]. In order to determine mechanical properties of welded joint metal, bend testing of samples with a sharp notch along the joint line was performed. Results of mechanical testing of welded joints are given in Table 1.

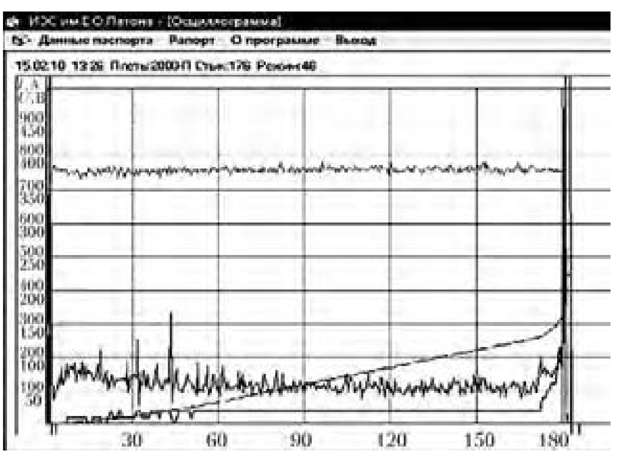

Figure 4. Oscillograms of the main parameters of welding in the soft FBW mode

Tensile testing of standard samples did not reveal any rejection indications, except for strength lowering by approximately 5.5 %. Sample fracture occurred at a distance of 21 mm from the joint plane. Bend testing of welded samples showed that at $v_{fin} = 1.1$ and 1.2 mm/s any rejection indications were absent. At $v_{fin} = 1.0$ mm/s cracks initiated in the joint plane, which by their length (not more than 6 mm) were not in the category of rejection indication by the normative documents [2, 3]. Bend angle of samples was equal to 180°.

Further lowering of final speed to 0.9 mm/s led to formation of cracks of the length not exceeding the value allowed by the standards. Testing of notched samples showed that such cracks are an indication of presence of sections of structural inhomogeneity that is characteristic for insufficiently intensive flashing before upsetting. In samples of welded joints made at $v_{fin} = 1.1$ and 1.2 mm/s, defects in the joint plane are absent on fracture surface. At $v_{fin} = 1.0$ mm/s,

Table 1. Mechanical properties of welded joints made at different final flashing speed*

Batch #	v_{fin}, mm/s	σ_t, MPa	Rejection indication
1	0.9	518.6	Cracks > 6 mm, $\sigma_t \le 94.5$ %
2	1.0	518.0	$\sigma_t \le 94.5$ %
3	1.1	518.4	
4	1.2	518.3	

*Here and in Table 2 bend angle was equal to 180°, 12 tensile samples and 30 bend samples were tested in each batch.

Table 2. Mechanical properties of welded joints made with different upset value

Batch #	Upsetting, mm	σ_t, MPa	Rejection indication
1	8	515.9	6 % softening
2	10	516.8	5.5 % softening
3	12	518.6	Same
4	14	518.3	»

individual fine defects appear, so-called mat spots of up to 20 mm^2. In butt joints welded at v_{fin} = = 0.9 mm/s, frequency of such defect occurrence becomes higher, and their area can reach 30–35 mm^2. Proceeding from the obtained results, a program with v_{fin} = 1.2 mm/s was accepted in further research.

In order to determine the optimum value of upsetting, four batches of pipe butts were welded in the basic «soft» mode with different upsetting. Each batch consisted of five butt joints: three were used to evaluate mechanical properties of the welded joint, and two were broken in the joint plane (Table 2). Obtained results of tensile testing of these specimens were practically identical. At their testing the reject indication was lowering of ultimate strength of up to 6 % with samples failing in the HAZ away from the joint plane. At bend testing of samples, cracks (small-sized delaminations within normative limits) appeared in some batches of joints welded with upsetting of 8–10 mm. Bend angle of these samples also corresponded to normative values (Figure 6). At bend testing with notches, microimperfections of the structure were found in fractures in the joint plane of some samples made with 8–10 mm upsetting (Figure 7), which were caused by local accumulation of non-metallic inclusions, namely manganese alumosilicates.

In welding of pipes with large developed cross-section, deformation of heated metal can be non-uniform. Therefore, l_{up} = 13 mm was taken as the optimum upsetting value. In order to achieve such deformation when the «soft» mode is used, specific upset force of 45 MPa is required.

Proceeding from investigation results, an optimum welding mode is given below, which can be reproduced in a production unit for welding pipes from 10G2FB steel 27 mm thick:

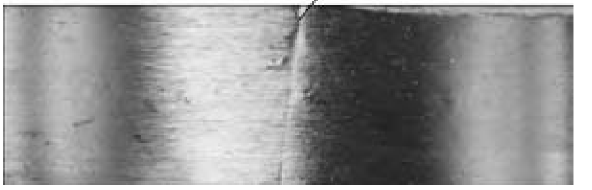

Figure 6. Crack in a sample tested for bending (α = 180°)

Secondary voltage, V	7
Welding time, s	180–210
Feed rate at heating, mm/s	0.19–0.20
Flashing allowance at heating, mm	32–38
Allowance for speed increase, mm	6–9
Final speed before upsetting, mm/s	1.2
Specific upset force, MPa	45
Upsetting, mm	13

The above mode was used to weld test batches of samples and perform mechanical testing in keeping with standards [2, 3]. Test results are given in Table 3, from which one can see that at rupture testing, ultimate strength of welded joints decreases by 5.5–6.0 %. This occurs in HAZ region, where heating temperature reaches 700–800 °C and is caused by lowering of the effect of steel heat hardening, achieved during its controlled rolling. Impact toughness values KCV_{+20} and KCV_{-20} of the joints do not meet the specified requirements [2, 3].

As is seen from Figure 8, the greatest lowering of impact toughness occurs in the local region in the weld center, the length of which is equal to l = 0.5–1.0 mm from the joint plane, that is confirmed by the conducted metallographic investigations. This is readily seen at comparison of the structures of base metal (Figure 9, *a*) and joint line with regions of coarse grain of up to 0.5 mm length adjacent to it (Figure 9, *b*), where metal was subjected to short-term heating up to the temperature of 1300 °C and higher. Base metal microstructure is a ferritic fine-grained matrix (ferrite grains, class 11) with carbide stringers which are elongated along the rolling direction (Figure 9, *a*). Structures with a considerable coarsening of bainite grain (class 3) and high content of polygonal ferrite form in the region adjacent to the joint plane.

Table 3. Mechanical properties of test batch of samples*

Test results	σ_t, MPa	KCV_{+20}, J/cm^2	KCV_{-20}, J/cm^2
After welding	516.0–523.4 / 520.0	13.3–17.1 / 15.0	6.1–9.7 / 8.1
After heat treatment	550.6–561.4 / 554.6	147.9–219.5 / 173.2	86.8–171.1 / 137.9

*Bend angle was 180°; no cracks.

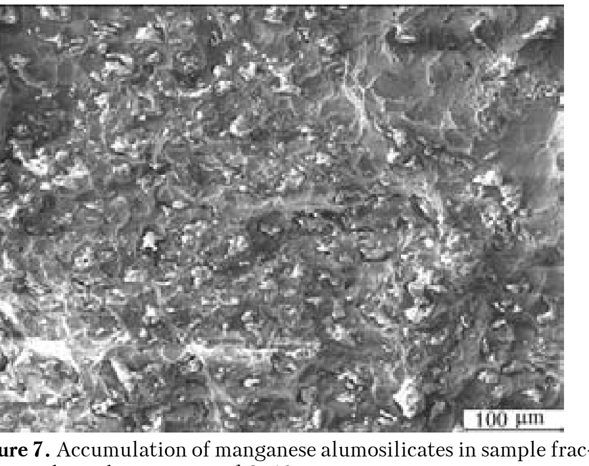

Figure 7. Accumulation of manganese alumosilicates in sample fractures made with upsetting of 8–10 mm

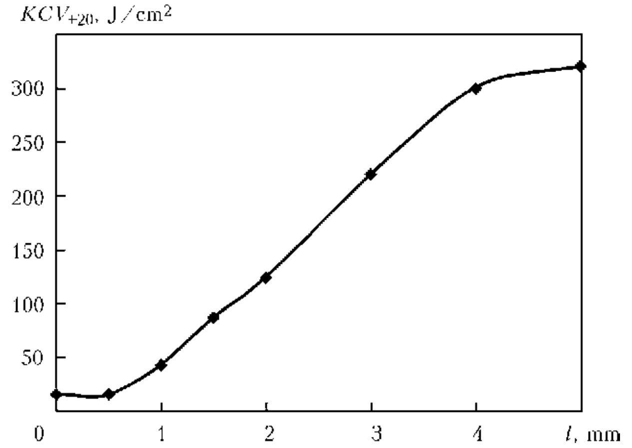

Figure 8. Distribution of impact toughness KCV_{+20} in the HAZ metal

These structures are characterized by low values of impact toughness.

In order to check the possibility of increasing the values of impact toughness and strength of welded joints, a batch of samples was welded in the «rigid» mode, the parameters of which are given below:

Secondary voltage, V	7
Welding time, s	45–50
Feed rate at heating, mm/s	0.3
Flashing allowance at heating, mm	12
Allowance for speed increase, mm	5–6
Final speed before upsetting, mm/s	1.2
Specific upset force, MPa	120–140
Upsetting, mm	5–6

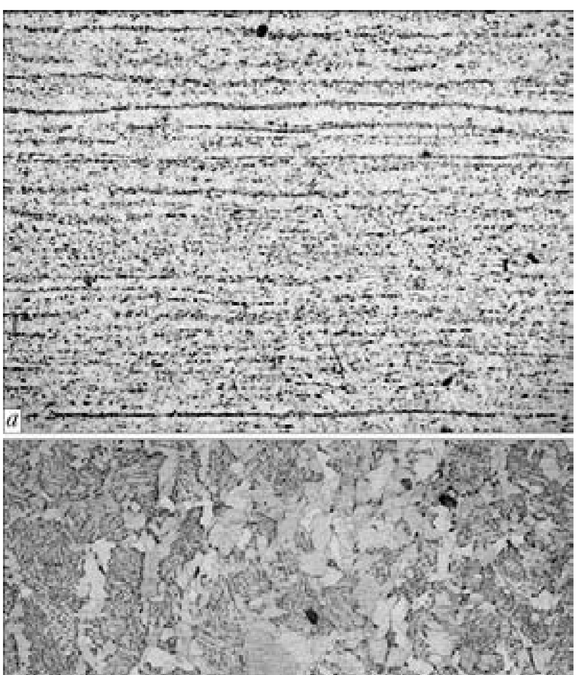

Figure 9. Microstructures (×100) of base metal of pipes (*a*) and metal of joint line with coarse grain regions (*b*)

The above mode features a shorter flashing duration in period *II*, increased final speed and greater specific pressure. Mechanical properties of metal of joints made in the «rigid» mode, are as follows: σ_t = = 546.0–553.6 MPa; KCV_{+20} = 16.3–22.6 J/cm²; KCV_{-20} = 6.1–9.7 J/cm²; bend angle was equal to 180°; cracks were absent. In welding in the «rigid» mode total process duration is reduced to 50 s, flashing allowance — to 12 mm, and power consumed in the final period of welding increases up to 23 V·A/mm², i.e. it is almost 2 times higher compared to the «soft» mode. All the other indices correspond to normative requirements except for impact toughness, which increased slightly as a result of lowering of polygonal ferrite content and refinement of primary austenite grains, but its values are below the normative level [2, 3].

In view of the fact that the «rigid» mode requires an essential increase of consumed power at flashing, and great upsetting forces, but only slightly increases welded joint impact toughness, its application is not rational.

It is known that in order to increase the ductile properties of welded joints made by FBW, it is necessary to apply high-temperature heat treatment [8]. In this connection, investigations were performed and technology was developed for heat treatment of welded joints of thick-walled pipes. Samples of welded joints, made in the reference mode, were subjected to local heating by a circular inductor with 2.4 Hz frequency, using thyristor frequency converter TPChT-160. Heating was performed up to the temperature of 950 °C for 5 min, soaked at this temperature for 2.5–3.0 min, and then samples were cooled in an accelerated mode by water-air mixture from two sides up to approximately 300 °C. Accelerated cooling is required, as it eliminates lowering of hardness and ultimate strength in the heating region.

After heat treatment and accelerated cooling of butt joints in the above mode, ultimate strength of welded joints corresponded to base metal values (see Table 3). Bend angle of samples was 180°, cracks on

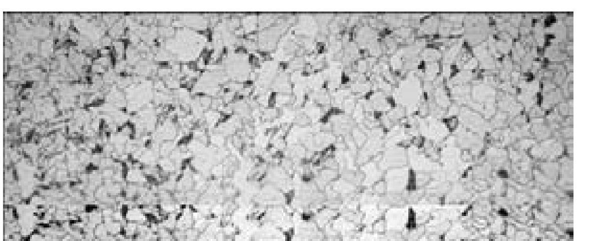

Figure 10. Microstructure of metal (×400) of joint line with coarse grain regions after heat treatment and accelerated cooling

the joint line and in the HAZ were absent. Impact toughness KCV_{+20} and KCV_{-20} was equal to 173.2 and 137.9 J/cm^2, respectively. These indices are by an order of magnitude higher than impact toughness values of the joints after welding. Mechanical properties of the joints after heat treatment and accelerated cooling fully comply with the requirements of both Russian [2] and international standards [3].

Microstructure of metal of the joint line and coarse grain region is a ferritic matrix with inclusions of residual austenite, which partially decomposes with granular bainite formation. Microstructure of the joint line and coarse grain regions after heat treatment is shown in Figure 10.

Ferrite grain is class 9. Hardness along welded joint line and in the HAZ is on the level of $HV5$ 1900 ± ± 50 MPa that does not exceed the required values [2, 3].

Postweld local heat treatment and accelerated cooling allow leveling the disadvantages of mechanical properties of the joints due to improvement of weld metal structure.

CONCLUSIONS

1. Technology of FBW of pipes from high-strength stainless steels of strength class K56 with up to 27 mm wall thickness was developed. In order to obtain sound joints of pipes from such steels, it is necessary for the power source and welding machine upset drive to ensure the values of consumed specific power of not less than 12 V·A/mm^2, and specific upset force of not less than 45 MPa in welding.

2. Integrated mechanical testing and metallographic investigations of pipe steel welded joints were conducted. Application of high-temperature heat treatment (normalizing) after welding in combination with accelerated cooling ensures meeting the standard requirements.

3. Proceeding from the results of the conducted studies, statements of work on development of new generation equipment for FBW of thick-walled pipes of 1220–1420 mm diameter were prepared.

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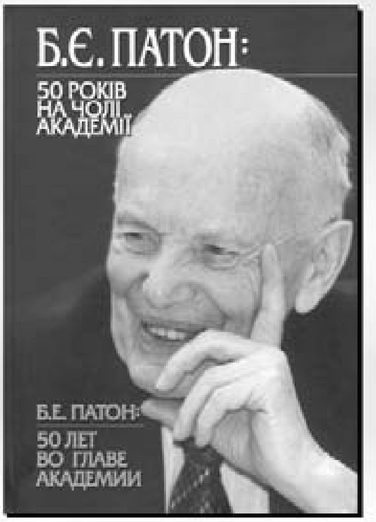
NEW BOOK

(2012) **B.E. Paton: 50 years at the head of the Academy.** — Kyiv: Akademperiodyka, 2012. — 776 p., 136 p. ill. (in Ukr. and Rus.).



The book highlights 50 year of activity of academician Boris E. Paton, outstanding Ukrainian scientist and research organizer, in the position of President of the National Academy of Sciences. Well-known scientists, including academicians A.P. Aleksandrov, G.I. Marchuk, Yu.S. Osipov, N.M. Amosov, Zh.I. Alfyorov, N.V. Bagrov, O.M. Belotserkovsky, P.A. Vityaz, D.M. Grodzinsky, L.V. Gubersky, I.M. Dzyuba, M.Z. Zgurovsky, E.N. Kablov, V.G. Kadyshevsky, N.N. Kudryavtsev, Yu.I. Kundiev, N.P. Laverev, N.V. Novikov, B.I. Olejnik, V.V. Panasyuk, Yu.N. Pakhomov, E.M. Primakov, V.A. Sadovnichy, A.M. Serdyuk, K.M. Sytnik, V.V. Skorokhod, A.A. Sozinov, V.I. Starostenko, B.S. Stogny, V.Ya. Tatsy and P.P. Tolochko share their impressions from their personal communication with B.E. Paton, his great influence on development of science and engineering. The book is illustrated with numerous photos.

It can be useful to all who are interested in the history of science.