doi.org/10.15407/tpwj2017.08.06

JOINT FORMATION IN MAGNETICALLY-IMPELLED ARC BUTT WELDING OF THICK-WALLED PIPES FROM HIGH-STRENGTH STEELS

V.S. KACHINSKY and **S.I. KUCHUK-YATSENKO**
E.O. Paton Electric Welding Institute, NASU
11 Kazimir Malevich Str., 03680, Kiev, Ukraine. E-mail: office@paton.kiev.ua

Searching for highly-efficient technologies of welding position butt joints of pipes is especially urgent, particularly during operation performance in site. The paper gives the results of comprehensive research on optimization of the technology of pressure welding of pipes with more than 4–5 mm wall thickness, using a controlling magnetic field. Methods of heating pipe edges by magnetically-impelled arc, algorithms of controlling the main parameters of pressure welding have been determined and comprehensive testing of the joints has been performed. Possibility of achieving high values of welded joint impact toughness in welding high-strength pipe steels is shown. 10 Ref., 7 Figures, 5 Tables.

Keywords: *pressure welding, controlling magnetic field, magnetically-impelled arc, thick-walled pipes, welding technology, site and stationary conditions, mechanical properties*

Ensuring stable quality of position butt welded joints of steel pipes made by highly efficient technologies is an urgent goal for companies in different countries, whose business is associated with pipe welding. Also important is lowering of welder's impact on the technological process.

The above-noted is especially relevant when making joints of pipes with greater (more than 4–5 mm) wall thickness, as well as when it is required to make joints in site.

This work is a study on enhancing the capabilities of pressure welding, in particular, under the impact of external controlling magnetic field (CMF). The following aspects were studied:

- behaviour of welding arc in a narrow gap of approximately 2 mm, between the edges of thick-walled pipes under the impact of external CMF;
- speed of arc movement during heating of thick-walled pipe edges;
- features of heating of thick-walled pipe edges;
- behaviour of liquid melt during pipe heating;
- influence of liquid melt on welded joint formation.

Technology of welding pipes with more than 4–5 mm wall thickness and equipment for magnetically-impelled arc butt pressure welding (MIABPW) of pipes in stationary and in site conditions were developed.

Technology application areas are as follows: welding gas and oil pipelines; welding tubes for systems of thermal stabilization of soil at down to –40 °C ambient temperature (more than 7 thou km of tubes have been welded, which keep all in all 25 mln m^3 of soil in the frozen state over an area of 2.5 mln m^2) hot house construction (more than 50 thou butt joints of tubes have been welded); industries, where butt welding of pipes to fittings, plugs, etc. is applied; welding tubular billets in manufacture of hydraulic cylinders (more than 17 thou butt joints have been welded).

The main features of MIABPW technology include the possibility of welding steel pipes in air, without using shielding gases, as well as implementation of technology of MIABPW of pipes with wall thicknesses greater than the dimensions of active spots of powerful arc discharges.

In application of MIABPW process, the welding arc moves under the impact of an external constant magnetic field. This welding method is applied in industry predominantly for joining parts of a tubular cross-section with up to 4 mm wall thickness and up to 100 mm diameter for automotive industry, with application of shielding gases [1–4]. PWI developed MIABPW technology and welded more than 7 mln hollow parts of automotive range without shielding gas application [5]. Development of technologies and equipment for MIABPW of various pipelines was performed [6]. Despite the high efficiency and other technological advantages, compared to electric arc methods, MIABPW process still has not become widely accepted in industry in critical power engineering plants, in particular, in boiler construction, high pressure gas and oil pipelines. This is largely due to limited information on mechanical properties of welded joints, made by MIABPW, as well as absence

Table 1. Chemical composition of steels, wt.%

Steel grade	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Ti	Nb	Al
09G2S	0.11	0.75	1.38	0.015	0.016	0.05	0.05	0.25	0.05	–	–	0.01
35	0.39	0.35	0.75	0.035	0.04	0.25	0.25	0.25	–	–	–	–
X70	0.030	0.156	1.45	0.004	0.004	0.30	0.14	0.07	0.20	0.022	0.062	–
01Star520	0.159	0.172	1.19	0.012	0.006	0.13	0.04	0.04	0.03	0.002	0.002	0.03
STPG410	0.25	0.34	0.9	0.024	0.033	–	0.001	0.001	–	–	–	–

of technology of MIABPW of pipes with more than 5 mm wall thickness.

Investigations conducted in this work were aimed at development of technology and equipment for MIABPW of position butt joints of pipes with 10–20 mm wall thickness from high-strength steels and development on their basis of the technology of welding up to 320 mm pipes with wall thickness, exceeding the dimensions of arc active spots, adapted to operation in site and under stationary conditions. Pipes from different steels were welded, in particular, X60, X70, X80, St35, STPG410, 01Star520. Table 1 gives chemical composition and mechanical properties of steels. Welding was performed in MIABPW machines of MD1, MD-205 type, developed at PWI.

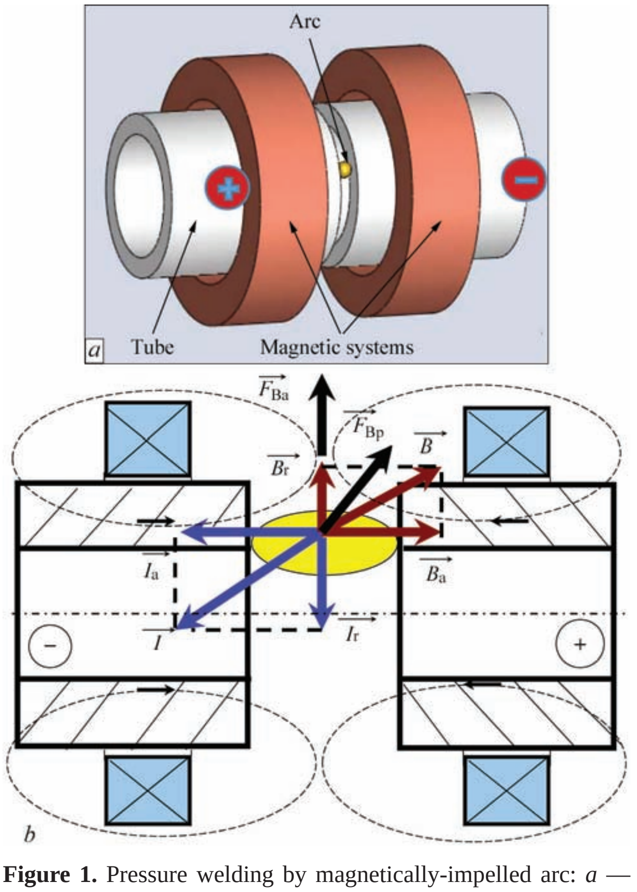

Figure 1. Pressure welding by magnetically-impelled arc: *a* — process schematic; *b* — forces applied to the arc ($\vec{B}$ — magnetic field induction; $\vec{B}_a$ — axial component of magnetic field induction; $\vec{B}_r$ — radial component of magnetic field induction; $\vec{I}$ — arc current; $\vec{I}_a$ — axial component of arc current; $\vec{I}_r$ — radial component of arc current; $\vec{F}_{Br}$ — force determining radial movement of the arc along pipe edges; $\vec{F}_{Ba}$ — force determining axial motion of the arc along pipe edges)

During welding operational control of the main process parameters, namely current, voltage, displacement and deformation force during upsetting, was performed. Processes running in the arc gap between the parts, were studied using high-speed video filming with a high resolution (up to 4500 fps), as well as oscillographing of the process. Welded joints were tested in keeping with the requirements of international standards for gas and oil pipelines (API, DNV).

Metallographic studies of welded joints were performed in «Neophot 32» optical microscope.

MIABPW process schematic is given in Figure 1, *a*. Under the impact of a powerful magnetic field, the arc moves in the gap between the edges of pipes being welded and heats them. Heating intensity is determined by arc current and rotation speed. After the required heating temperature has been reached, part edges are pressed together and the joint forms during their deformation.

As with other pressure welding methods, in order to produce sound joints in MIABPW, it is necessary to create the specified temperature field, and protect the part edges being heated. It is assumed [7, 8] that metal vapours formed at heating by the arc, create partial protection from oxidation in the gap. It is considered [4] that stable heating and protection of part edges from oxidation can be obtained only in the case, when diameter of active arc spots is identical to thickness of pipes being welded. Therefore, up to now MIABPW process was practically used for joining pipes with not more than 5 mm wall thickness that corresponds to the dimensions of active spots of powerful arc discharges, which can be obtained at currents of 1–2 thou A.

Technologies developed at PWI are based on the concept [9], in keeping with which at MIABPW, similar to flash-butt welding (FBW), the main condition for producing sound joints is formation of a layer of molten metal with oxides of its alloying elements, on the edges of parts being welded in the period prior to upsetting. As a result of melt heating by rapidly moving arc, it has a higher temperature than that of melting of the material being welded. It is experimentally established that at contact melting of steels the melt reaches the temperature of 1700 °C. Its solidification proceeds in the range of 1700–1370 °C. If deformation of heated part edges takes place in this period, the melt is completely pressed out of the butt together with the oxides. Duration of melt solidification period depends on thermophysical properties of materials being welded and accepted welding technology:

$$t_1 = \frac{\delta_1 \gamma q}{\lambda \frac{d\theta}{dx}_{x=0}}, \qquad (1)$$

where t_1 is the duration of solidification; δ_1 is the melt layer thickness; $d\theta/dx_{x=0}$ is the gradient of temperature field in near-contact layer; λ is the thermal diffusivity; q is the deposited metal heat content at temperatures, exceeding its melting temperature.

At selection of welding technology, it is possible to vary the conditions of part heating and partially — value δ_1. The most favourable conditions for formation of sound joints in the joint plane are in place in welding with minimum temperature field gradient that is associated with large energy input into the heating zone, and is unfavourable for formation of metal structure in the HAZ, particularly in welding high-strength steels. Therefore, searching for optimum technologies of MIABPW of above-mentioned steels was aimed at development of technologies, featuring minimum energy input and high gradients of HAZ temperature field.

Investigation of processes running in the arc gap at heating of pipe edges by a moving arc was performed on pipes of up to 320 mm diameter with up to δ = 12 mm wall thickness using high-speed video filming. The main parameters of the process (CMF induction, arc current, voltage) were varied within the range of values accepted at MIABPW of such pipes. MIABPW is performed both using constant magnets and electric magnets. Constant magnetic systems were applied in production units developed at PWI.

Figure 2 shows photographs illustrating arc behaviour in the gap and edges heating in different periods of MIABPW of pipes. Arc current was equal to 200–250 A, arc voltage was U_a = 25 V. After arc excitation in the gap between the edges, the speed of arc movement is constantly rising, reaching from 50 to 240 m/s by the moment of upsetting performance, depending on pipe diameter, and pipe heating is performed (Figure 2, *a*). As edges temperature rises, melt thickness on them increases (Figure 2, *b*), the melt being retained on the surface of edges by surface tension forces. After a certain thickness has been reached, the melt starts moving in the same direction, under the impact of forces rotating the arc along the edges being heated (Figure 2, *c*). Adjustable speed of this movement can reach 3 m/s under certain conditions. Melt motion is due to the impact of electrodynamic forces and gas pressure in the arc gap, excited by moving arc column. Here, mixing of molten metal layer proceeds. Prior to upsetting, melt layer on the edges is quite uniformly distributed around the pipe perimeter and across its edge thickness (Figure 2, *d*). In the initial upsetting period, the gap between the edges decreases, and the arc discharge is stopped for the period of gap closing (Figure 2, *e*), which is 0.01 s long at upsetting speed of 200 mm/s. At gap reduction to the value of $2\delta_1$, a continuous interlayer of metal melt starts forming between the edges (Figure 2, *f*), which continues its circular motion under the magnetic field impact (current supply through the edges is not interrupted). This promotes melt replenishment and formation of a continuous interlayer across the entire section of pipes being welded. At the moment of gap closing, the melt is pressed out of the butt, and

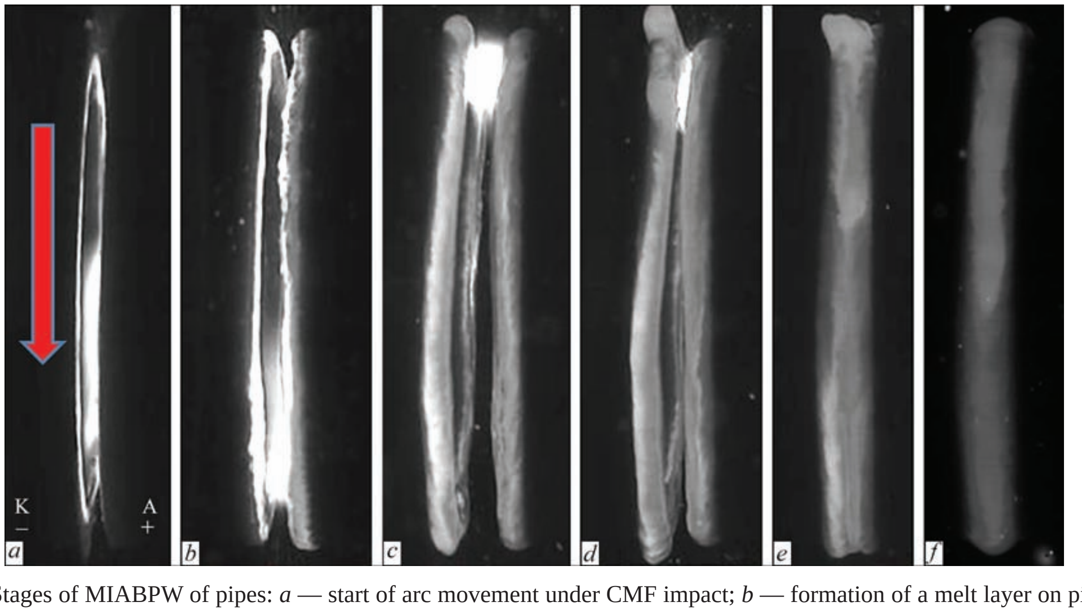

Figure 2. Stages of MIABPW of pipes: *a* — start of arc movement under CMF impact; *b* — formation of a melt layer on pipe edges; *c* — melt movement during heating; *d* — melt replenishment before upsetting; *e* — upsetting start; *f* — welded joint formation

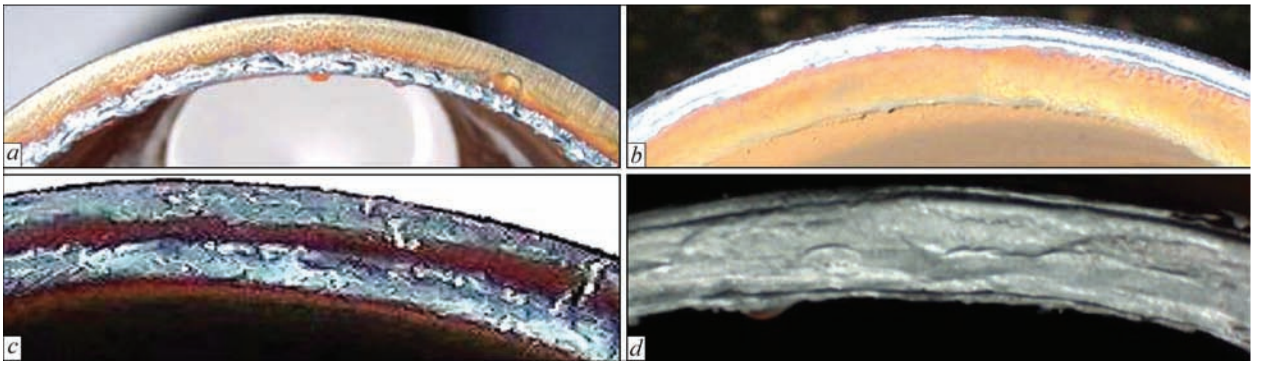

Figure 3. Control of arc movement on the surface of pipes being welded: *a* — arc moves along inner pipe edges; *b* — arc moves along outer pipe edges; *c* — arc scanning from pipe inner to outer edges; *d* — formation of a melt of stable thickness on pipe edges

deformation of heated metal layers in the solid phase takes place.

Given data show that melt behaviour in the period prior to upsetting, has a dominant influence on joint formation in MIABPW. In this period measured in hundredth of a second, the edge surface is not exposed to direct impact of the arc and is in contact with ambient air, surrounding the welding zone. Here, the area of the regions covered by liquid melt, can be much greater than that of the arc active spots, that leads to the conclusion about the possibility of forming sound joints in the regions of edges at sufficiently long periods of interruption of arc passage through these regions. This conclusion was the base for development of the technology of MIABPW of pipes with wall thickness much greater than the dimensions of active spots of powerful arcs.

Performed research of fast processes of melt behaviour in the gap at MIABPW was the base for development of algorithms for controlling MIABPW process parameters in different welding periods. Welding program envisages two periods. In the first period pipe heating takes place, which provides the specified temperature field and edge deformation. In the second period, preceding deformation (upsetting), formation of the melt is ensured in the gap, which is stable by thickness and is kept in the molten state due to intensive energy input. For this purpose, the process is briefly switched into arc contact heating mode that is accompanied by power increase. To provide a stable heating uniform across pipe thickness, as well as required conditions of melt formation in welding thick-walled pipes, PWI developed a system of arc movement control, the schematic of which is given in Figure 1, *b*.

After arc excitation in the gap between pipe edges, stable movement along the inner edge of pipe perimeter is provided, as a result of the impact of radial component $\vec{B}_r$ of magnetic flux induction (Figure 3, *a*). Stable movement of the arc along the pipe outer edge is ensured under the impact of axial component $\vec{B}_a$ (Figure 3, *b*). Periodical change of the value of above-mentioned components leads to scanning movements of the arc between the pipe outer and inner surfaces (Figure 3, *c*). Here, uniform heating of edges in the first period and melt formation in the second period are provided (Figure 3, *d*).

Analysis of mentioned features of heating by quickly moving arc allowed establishing the optimum program of controlling MIABPW parameters.

Based on the above-mentioned studies, PWI developed technologies of MIABPW of high-strength pipes of 60 to 219 mm diameter with 6–16 mm wall thickness. Table 1 gives chemical composition of some pipes in this category, Table 2 shows the main comparative parameters characterizing welding modes in MIABPW and FBW. Table 3 presents the main process parameters in MIABPW of pipes and gives similar parameters for comparison, which characterize the technology of joining similar pipes by flash-butt welding, developed at PWI.

Comparison of the given data shows that duration of the processes, as well as power consumed in MIABPW and FBW of pipes of the same dimensions, differs only slightly that is indicative of identical thermal efficiency of the processes.

Table 2. Main process parameters at MIABPW and FBW

Steel type or grade	Pipe size, Dn, mm	Welding process	Welding time, s	Upsetting force, kN	Heating allowance, mm	Upsetting allowance, mm	Consumed power, first period, kV·A	Consumed power, second period, kV·A
X70	Ø168×7	MIABPW	34.7	247	0	7.5	19.6	58.7
		FBW	37.2	177	15	8	25.1	60.2
35	Ø76×16	MIABPW	105	241	0	10	22.4	64.6
		FBW	120	168	36	19	40.2	98.4

Table 3. Main process parameters of MIABPW of pipes

Steel type or grade	Pipe size, Dn, mm	Welding time, s	Upsetting force, kN	Pipe shortening, mm
X70	168×7	34.7	247	8.5–8.9
01Star520	121×7	27	200	8.8–9.2
01Star520	121×10	43	278	10.7–11.2
35	76×16	82	255	16.4–16.9
09G2S	42×4	14	40.6	3.9–4.1
STPG410	60.5×5.5	19	80	5.8–6.8

In MIABPW, metal losses for flashing are much lower, than in FBW, but 1.5 times greater upsetting forces are required to produce sound joints. The latter is indicative of lower temperature of metal layers, subjected to deformation during upsetting. Formation of welded joints of pipes from X70 steels of 168×7 mm size by MIABPW, is shown in Figure 4. Control of pipe upsetting allowance enables significant reduction of welded joint reinforcement height, which is equal to 0.8 to 1.8 mm.

Mechanical testing of pipe joints made by MIABPW, which was performed in keeping with requirements of API and DNV standards, showed that strength and ductility properties of the joints are on the level of base metal values (Tables 4, 5).

As is known [10], an abrupt lowering of impact toughness values is observed at different methods of pressure welding of the above-mentioned steels, including FBW, particularly at low testing temperatures. Producing the required ductility properties of such joints requires additional heat treatment. All the joints of the above-mentioned pipes (Tables 2, 3) welded by MIABPW without heat treatment, had impact toughness values at testing temperatures of 20; –20; –40 °C not lower than 80 % of the respective base metal values.

Figure 4. Welded joint formation in MIABPW

This is achieved primarily due to energy input in welding and regulation of melt movement in the arc gap in the period, preceding deformation of heated edges prior to upsetting. Formation of a melt stable across the thickness δ_1 on pipe edges enabled producing sound joints at higher gradients of temperature field in near-contact region (Figure 5).

Temperature of near-contact layers and metal softening are reduced, respectively. Figure 6 gives the temperature fields in the heating zone in MIABPW and FBW of pipes of 168 mm diameter, δ = 7 mm. Heating temperature of near-contact layers at 2 mm distance from the melting surface at the moment be-

Table 4. Mechanical properties of base metal and welded joint of pipes at MIABPW and FBW

Steel type (welding process)	σ_y, MPa	σ_t, MPa	KCV_{+20}, J/cm^2	KCV_{-20}, J/cm^2
X70	448.9–469.1 460.6	528.8–566.8 551.0	248.4–265.7 256.5	248.4–265.7 256.5
X70 (MIABPW)	411–440 425.5	532–548 540	124.8–253.4 189.1	149.3–244.4 196.8
X70 (FBW)	–	536–543 539	31.6–238.4 134.5	29.2–141 85.3

Table 5. Mechanical properties of pipe welded joints

Steel type or grade	Pipe size Dn, mm	Base metal σ_t, MPa	Welded joint σ_t, MPa	Base metal KCV_{+20}, J/cm^2	Welded joint KCV_{+20}, J/cm^2	Base metal KCV_{-20}, J/cm^2	Welded joint	
							KCV_{-20}, J/cm^2	KCV_{-40}, J/cm^2
09G2S	42×5	460–478 469	453–484 465	57–5 58	59–78.1 68.5	57.8–58 57.9	64–74.5 69.3	–
35	89×10	538–565 551	528–554 541	56–64 60	52–965 70	–	–	–
01Star520	191×7	638–665 651	618–674 656	116–154 135	87–152 119	–	–	–
STPG410	60.5×5.5	452–464 458	450–462 456	90–98 94	86–92 89	102–104 98	87–94 91	88–94 92

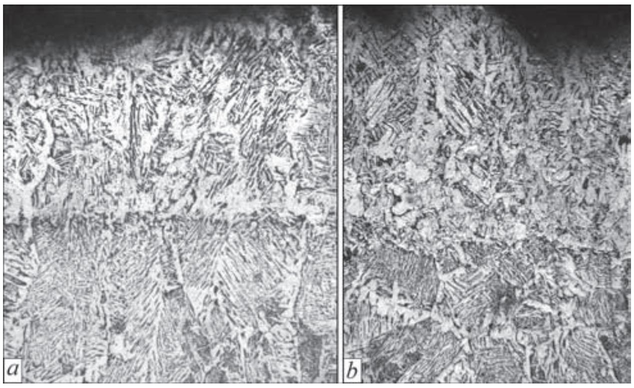

Figure 5. Microstructure of cast metal at the cathode (*a*) and anode (*b*) (×200)

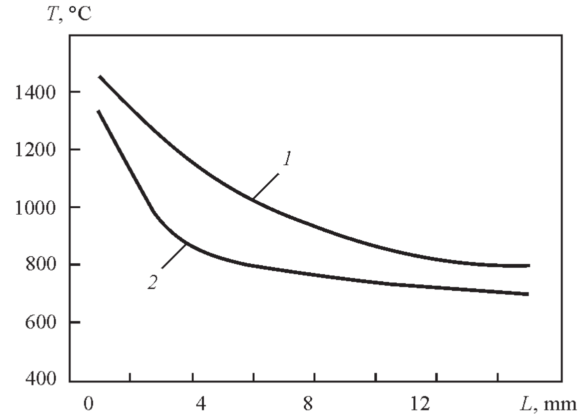

Figure 6. Temperature distribution at FBW (*1*) and MIABPW (*2*) (distance from the butt is given)

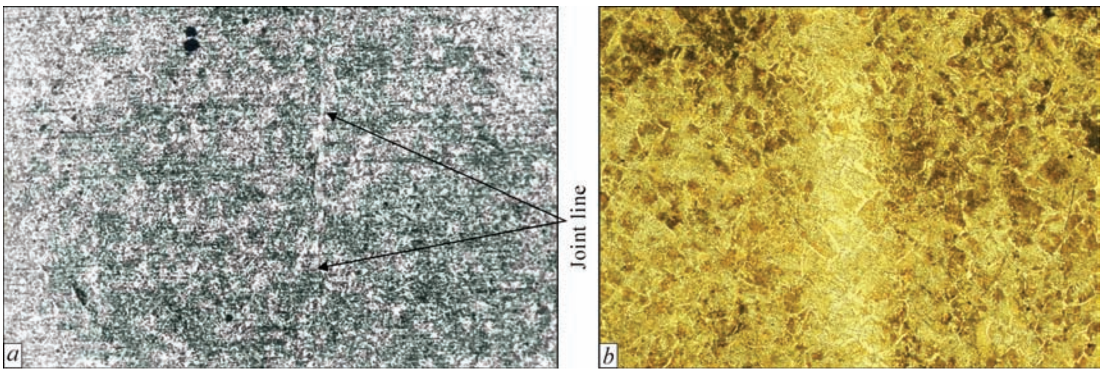

Figure 7. Microstructure of welded joints: *a* — at MIABPW (×150); *b* — at FBW (×100)

fore the start of deformation in MIABPW is equal to not more than 1050 °C, and in flash-butt welding of such pipes it is by 100 °C higher. It is experimentally established that an abrupt lowering of *KCV* values is observed at fast heating of samples from X70 steel up to the temperature of 1100–1150 °C.

As during deformation the structure of the weld central part and along the joint line is determined by the structure of these layers, temperature distribution given in Figure 6 (curve *2*), seems to be optimum at different pressure welding methods, in order to achieve high *KCV* values. Figure 7, *a* shows microstructure of a joint of pipes of 168 mm diameter, $\delta = 7$ mm, from X70 steel, made by MIABPW in the optimum mode (Table 2). Metal along the welding line has ferritic-pearlitic structure with ferrite precipitates in the form of an intermittent band of up to 10 μm thickness. In the central part the structure is fine-grained (grain size number 8, 9) with hardness *HV* 2470–2640 MPa. Total width of the HAZ in MIABPW was equal to 10 mm. For comparison, Figure 6, *b* gives an analogous structure in welding similar pipes by FBW. Structure along the welding line is coarse-grained (grain size number 3–5) with prevalence of pearlitic component and multiple clusters of polygonal ferrite, width of ferrite band being 100 μm. In this region lowering of hardness by 10 %, as well as of impact toughness, is observed, that is the consequence of overheating of near-contact regions up to temperatures of more than 1200 °C, in which formation of the weld took place (curve *1* in Figure 6).

Total width of the HAZ in FBW was equal to 18 mm. Sound joints at heating corresponding to curve *2* in Figure 6, were produced only at MIABPW. Application of such a heating mode at FBW leads to formation of defects along the joint line in the form of thin oxide films, although microstructure in the weld center is similar to that obtained at MIABPW. Possibility of producing sound joints at MIABPW at higher gradients of temperature field is due to formation of a melt stable across the thickness in the gap.

Minimum melt thickness at MIABPW of pipes is equal to 0.6 mm, and at FBW melt thickness varies in the range of 0.15 to 0.2 mm. In keeping with expression (1) formation of sound joints in MIABPW can be achieved at higher gradients of the temperature field in the HAZ. The given data are indicative of the fact that sound joints of high-strength steels in different pressure welding processes can be produced at relatively low temperature of heating of near-contact metal layers, if, alongside application of high-power density heat sources, formation of a melt stable across the thickness is ensured in the contact between the parts being welded, prior to upsetting.

Conclusions

It is found that the dominating factor determining formation of joints in MIABPW, is presence of a melt layer on pipe edges in the initial period of upsetting.

Methods were determined for uniform heating of pipe edges by a rotating arc, the thickness of which exceeds the diameter of the arc active spot.

Algorithms of control of the main parameters of MIABPW and process modes ensuring sound welding of high-strength pipes of up to 320 mm diameter with up to 16 mm wall thickness, were determined.

Comprehensive testing of joints of thick-walled pipes from high-strength steels made by MIABPW, has been performed, confirming strength of welded joints equivalent to that base metal and their high ductility properties. Possibility of achieving high values of impact toughness in MIABPW of high-strength pipe steels without heat treatment was determined.

Technologies for MIABPW of various pipes from high-strength steels of 20 to 320 mm diameter with up to 16 mm wall thickness were developed.

1. Hagan, D., Riley, N. (1979) MIAB welding. Part 2. Fabrication the Fiesta rear axle. *Metal Construction*, 625(**12**), 627–629.
2. Ganovski, F.J. (1974) The magnetarc welding process. Weld. Met. Fab., **June**.
3. *Kenji* Takagi, Hirokazu Otsuka, Fumiho Abakida et al. (1987) Establishment of optimum welding conditions of magnetically impelled arc butt welding and application to field operation. *IIW Doc. III–8801*.
4. Edson, D.A. (1982) Magnetically impelled arc butt welding of thick wall tubes. Ibid., *III-726–82*.
5. Kuchuk-Yatsenko, S.I., Kachinsky, V.S., Ignatenko, V.Yu et al. (2010) Magnetically-impelled arc butt welding of parts of automobile range of products. *The Paton Welding J*., **6**, 28–31.
6. Takagi, K., Aracida, F. (1982) Magnetically impelled arc butt welding of gas pipeline. *Metal Construction*, **10**, 542–548.
7. Gelman, A.S. (1950) *Resistance welding*. Moscow: Mashinostroenie.
8. Orlov, V.D., Dmitriev, Yu.V., Chakalev, A.A. et al. (1975) *Technology and equipment of resistance welding*. Moscow: Mashinostroenie.
9. (1992) *Flash-butt welding*. Ed. by S.I. Kuchuk-Yatsenko. Kiev: Naukova Dumka.
10. Kuchuk-Yatsenko, S.I., Shvets, Yu.V., Zagadarchuk, V.F. et al. (2012) Flash-butt welding of thick-walled pipes from high-strength steels of K56 strength class. *The Paton Welding J*., **5**, 2–7.

Received 02.06.2017