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MIAB WELDING TECHNOLOGY OF PIPES AND PARTS OF AUTOMOTIVE INDUSTRY

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ABSTRACT

The purpose of the research presented in this article is to develop a technology for press magnetically impelled arc butt welding (MIAB welding) using a pulsed increase in welding current and controlled precision allowance of the upset during the formation of joints of pipe steels and parts of the automotive industry. The main attention is paid to reducing energy consumption while ensuring high-quality welded joints. During welding, operational control of the main technological parameters was carried out: welding current, voltage, displacement and force at the moment of upset. To study the processes occurring in the arc gap between the ends of the pipes, high-speed video recording with a resolution of up to 4500 frames/s, as well as oscillography of the welding cycle parameters, was used. The resulting welded joints were tested in accordance with the requirements of international standards for gas and oil pipelines (API, DNV), which allowed assessinging their mechanical characteristics, reliability, and compliance with industrial application requirements.

KEYWORDS: technology of magnetically impelled arc butt welding, radial component induction of the control magnetic field, pulsed welding current, controlled upset allowance, formation of pipe joints

INTRODUCTION

MIAB welding is an innovative process that combines the advantages of heat treatment and mechanical butt welding of steel pipes and tubular parts. Process has found application in various industries due to its high productivity, stability of the quality of welded joints, as well as a high level of mechanization and automation of the technological process. The peculiarity of the automatic mode of MIAB welding is to significantly reduce the influence of the human factor on the quality of joints, which makes it especially effective for the manufacture of structures of critical purpose.

During the research, it was found that the influence of thermal and deformation cycles with the use of pulsed increase in welding current before the upset and the implementation of a controlled upset allowance contributes to the formation of joints with optimal characteristics according to the technical requirements of enterprises.

INDUSTRIAL APPLICATION

The main advantages of the MIAB welding process include high productivity due to the potentially high level of automation, as well as a reduction in the cost of manufacturing welded pipe joints. This process is particularly promising for use in the automotive industry, power plants, boiler production, pipelines for various purposes, oil refining and petrochemical plants, ships and other industries where liquids and gases are transported under high pressure and temperature, and where increased requirements are placed on the reliability and accuracy of welded joints.

Due to the short welding cycle and high reproducibility of the quality of joints, process is an effective solution for mass industrial production. The results of scientific research in the field of MIAB welding have been successfully implemented in practice. In particular, the results of a number of studies have been applied during the construction of pipelines, which confirmed the feasibility and effectiveness of implementing this process in industrial conditions [1–13]. MIAB welding technology and equipments developed at the E.O. Paton Welding Institute (PWI) have found practical use in welding pipelines with a diameter of up to 100 mm.

The MIAB welding is used in the automotive industry to join the drive shafts, cardan shafts, air springs, shock absorber assemblies and brake pipes. Industrial use in the automotive industry has been achieved by the development of technology and industrial equipment for Magnetarc welding by KUKA, Germany and for MIAB welding by PWI, Ukraine [14–16].

RESEARCH PROGRESS

For a comprehensive study of welding in a wide range of standard sizes of steel pipes and tubular parts with a diameter of Ø20–300 mm, K872, MD-205 and MD101 machines were used. Steel grades and their mechanical properties are given in Tables 2 and 4. Welding was performed in machines developed at the PWI. The experimental K-872 machine is shown in Figure 1.

The main technical characteristics of the pilot machines are presented in Table 1.

The K872 and MD205 installations include (Figure 2, *a*): welding machine (*1*), protection (*2*), pumping station (*3*), hydraulic system (*4*), computerized control system (*5*), welding current source (*6*), control panel (*7*), hydraulic hoses (*8*), electric cables (*9*). Figure 2, *b* shows the MD205 industrial installation for welding tubular parts of hydraulic cylinder bodies.

The design of the modernized MD101 machine with a developed hydraulic drive for welding pipes with a diameter of up to Ø60 mm is presented in Figure 3.

To carry out the work, the equipment was modernized in the following areas:

1. The hydraulic systems of the machines were improved with the possibility of a controlled upset with a given allowance.
2. A system for pulsed increase of the welding current before upset was developed.
3. The control program and the system for recording technological parameters of welding were improved to perform the above developments.

The block diagrams of the welding machine after modernization are shown in Figure 4.

To ensure the implementation of the quality control algorithm, the control system was modernized on the basis of an industrial computer. 3 Lincoln Linc 635SA welding rectifiers connected in parallel were used to power the arc. Supercapacitors were also used to create a pulsed increase in current [17].

FUNCTIONING OF THE CONTROL PROGRAM AND RECORDING OF TECHNOLOGICAL WELDING PARAMETERS

Preparation of the machine actuators for the welding process is carried out in the following sequence:

- turning on the control cabinet, starting the control program and recording parameters;
- turning on the pumping station and power source;
- installing pipes in the welding position.

After checking the compliance of the equipment state with the initial conditions for starting the process, the message “System ready” appears in the main window of the control program, indicating the readiness of the hardware for welding.

After pressing the “Welding” button, all remote controls are blocked, except for the “Stop welding” and “Emergency stop” buttons. The pipe welding process occurs automatically without the use of shielding gases.

A welding quality control algorithm has been developed based on the analysis of process parameters, covering three key stages:

1. Heating — the period of formation of the temperature field at the ends of the pipes being welded;
2. Welding current pulse — ensuring a protective environment in the arc gap due to intensive surface renewal;
3. Controlled upset — formation of a joint in the solid phase.

The conclusion about the quality of the produced welded joint with a certain degree of probability is made on the basis of logical rules formed based on the results of research into the technological features of the MIAB welding process.

The developed system for controlling and recording technological parameters of the welding process significantly expands the capabilities of personnel during the operation of welding equipment. It allows changing the settings and algorithms of the equipment’s operation without significant resource costs. In addition, the system provides remote monitoring of welding operations at remote sites, as well as quality control without the need for direct intervention in the production process [18].

The program window displays the technological parameters of the welding machine, which are controlled by the system.

It is possible to automatically switch to another welding mode in case of a change in the pipe diameter. During each start of the welding cycle, the system automatically performs the following actions:

- creates a technological process data file;
- forms a welding progress diagram;
- makes appropriate changes to the report file.

These operations are performed regardless of the progress of the welding process and are completed after its completion. Documentation of welding parameters is carried out in automatic mode, which allows:

- assessing the level of deviation of technological parameters from the specified values;
- correcting the parameters if necessary.

STUDYING THE INFLUENCE OF THE MAIN TECHNOLOGICAL PARAMETERS ON THE NATURE OF THE MIAB WELDING PROCESS

Studies of the processes occurring in the arc gap during heating of the pipe ends by an electric arc mov-

Table 1. Basic technical characteristics of machines power consumption, kVA

Machine type	Pipe diameter, mm	Wall thickness, mm	Productivity, joints/h	Upset force, kN	Power consumption, kVA	Weight, kg
MD101	10–61	1–5	120	40	30	230
K872	32–220	3–10	60	280	150	2700
MD205	32–240	3–11	60	350	170	2300

ing at high speed (up to V_a = 130 m/s) were carried out on tubular parts with a diameter of up to Ø200 mm and a wall thickness of up to δ = 10 mm. High-speed video recording was used to monitor the process.

The main parameters of the process — magnetic field induction, welding current and arc voltage — varied within the limits characteristic of the modes adopted for process when welding pipes of the specified type. At the same time, computer record of the specified parameters was carried out.

The studies carried out within the framework of this work were aimed at developing a technology for butt-joining of steel pipes adapted for operation in both field and stationary conditions. Welding was carried out on samples of various steel grades, in particular: X60, X70, X80, St35, 09G2S, JIS STPG410, ASTM A615 Grade 520. The chemical composition of the steels is given in Table 2.

Uniform heating of the surfaces of the pipes being welded is determined by the stability of the arc movement under the influence of an external control magnetic field (CMF). The speed of the arc movement depends on the following factors:

- the magnitude of the welding current;
- CMF induction;
- the gap between the pipe ends;

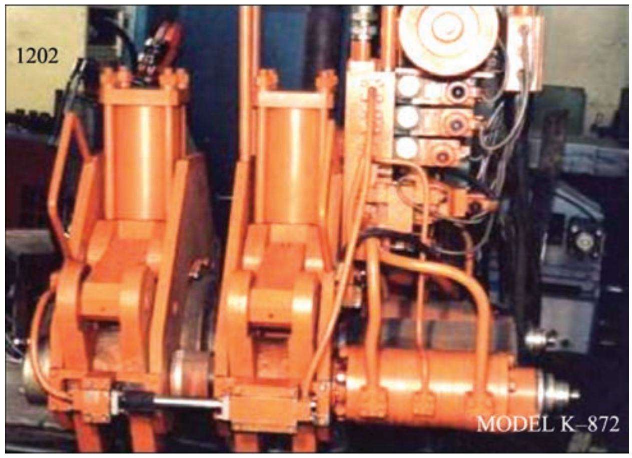

Figure 1. Machine K-872 for experimental studies

- the quality of edge preparation.

The position of the arc at the ends of the welded parts is determined both by the distribution of the control magnetic field induction and the influence of the ferromagnetic masses of the steel pipes on the arc. The results of the studies have shown that when welding steel products, the electric arc after excitation at the outer edges, under the influence of the ferromagnetic masses of the parts and the radial component of the CMF induction, is shifted in the arc gap to the inner region of the ends, Figure 5.

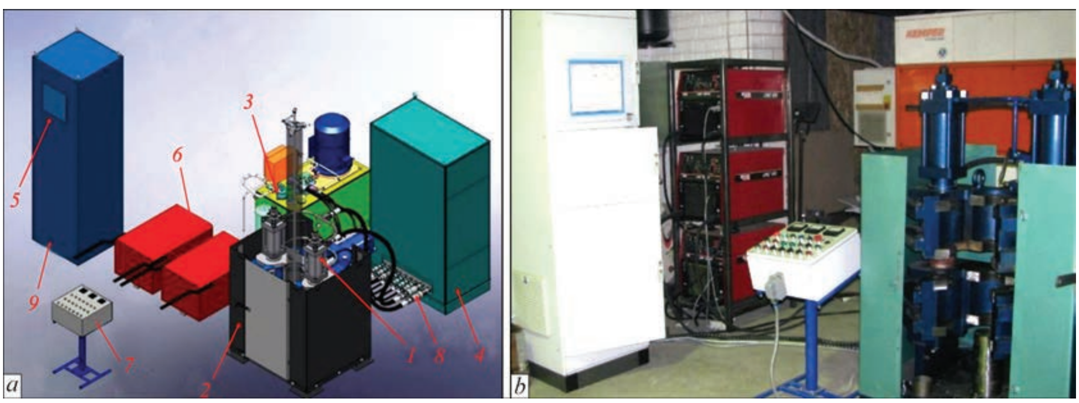

Figure 2. MD205 pipe welding machine, where: *a* — equipment for MIAB; *b* — MD205 machine in production

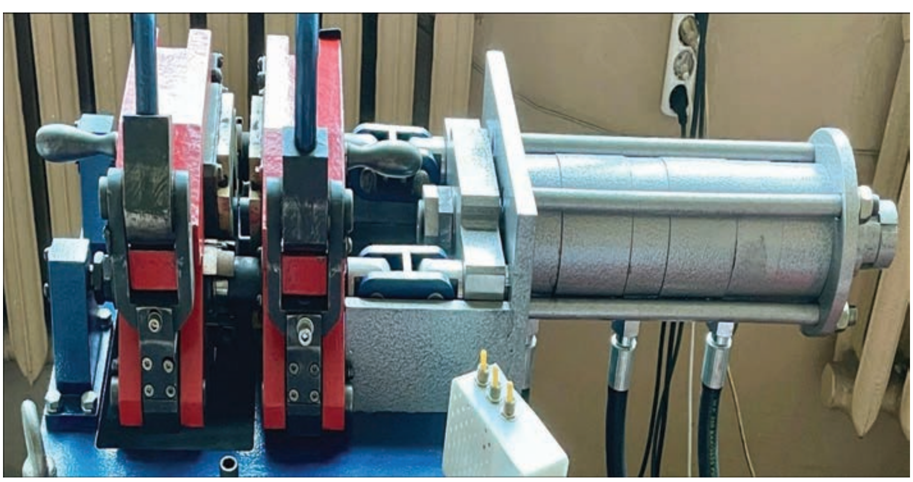

Figure 3. Machine MD-101

Table 2. Chemical composition of steels, %

Type steel	09G2S	St35	API X70	DIN 17100 St52-3	ASTM A615 Grade 520	JIS STPG410	ASTM A106/API5L
C	0.11	0.39	0.030	0.18	0.159	0.25	0.28
Si	0.75	0.35	0.156	0.52	0.172	0.34	0.25
Mn	1.38	0.75	1.45	1.35	1.19	0.9	1.20
P	0.015	0.035	0.004	0.02	0.012	0.024	0.030
S	0.016	0.04	0.004	0.03	0.006	0.033	0.030
Cu	0.05	0.25	0.30	0.28	0.13	-	0.50
Ni	0.05	0.25	0.14	0.24	0.04	0.001	0.50
Cr	0.25	0.25	0.14	0.24	0.04	0.001	0.50
Mo	0.05	–	0.20	–	0.002	–	0.15
Ti	–	–	0.022	–	0.002	–	–
Nb	–	–	0.062	–	0.002	–	–
Al	0.01	–	–	–	0.03	–	–

It was established that the optimal gap for welding pipes with a diameter of Ø150 mm is $\delta = 1.9\pm0.2$ mm. The results of the studies showed that when the CMF induction is less than $B_r = 70$ mT, the arc movement is unstable. An insufficient level of induction leads to oscillations of the arc column, especially when the pipes are horizontally placed, which causes local overheating and the formation of molten metal in the lower part of the welding zone. As a result, a crater is formed in the gap between the pipe ends (Figure 6).

Stable arc movement along the pipe ends is achieved when the radial component of the CMP induction is within $B_r = 110–180$ mT (Figure 7, *a*).

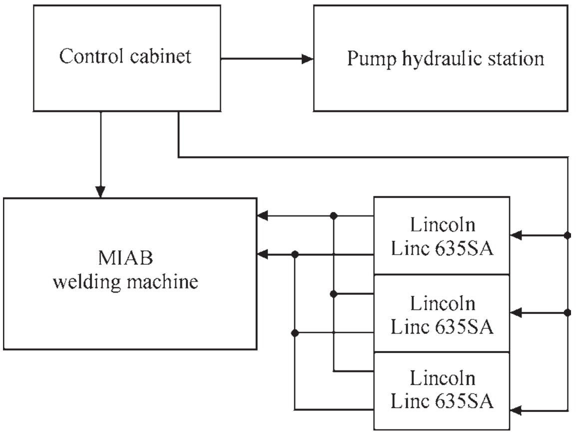

Figure 4. Block diagram of the welding machine

Figure 5. Displacement of the arc to the inner area of the butts

Under such conditions, relatively uniform heating of the ends is ensured, which is a necessary condition for plastic deformation of the material during upset (Figure 7, *b*).

The heating time with other parameters remaining constant is in a narrow range. Its value depends on the current and arc voltage, and a change in one of these parameters affects the change in the other. Excessive heating of the pipe ends can lead to the formation of liquid bridges between the pipes, which disrupts the stable movement of the arc in the gap.

The size of the arc gap largely determines the quality of welded joints. This parameter depends on the requirements for the stability of arc excitation and its stable movement. In the studied range of pipes, the value of the arc gap, as experiments have shown, varies within $\delta = 1.7–2.1$ mm. Figure 8, *a–f* shows photographs illustrating the behavior of the arc in the gap during heating of the ends at different stages of pipe welding.

The welding arc current was $I_a = 200–250$ A, the arc voltage $U_2 = 25^{\pm 2}$ V. After the arc is excited between the ends, the speed of its movement during heating constantly increases, from $V_a = 50$ m/s reaching $V_a = 240$ m/s depending on the diameter of the

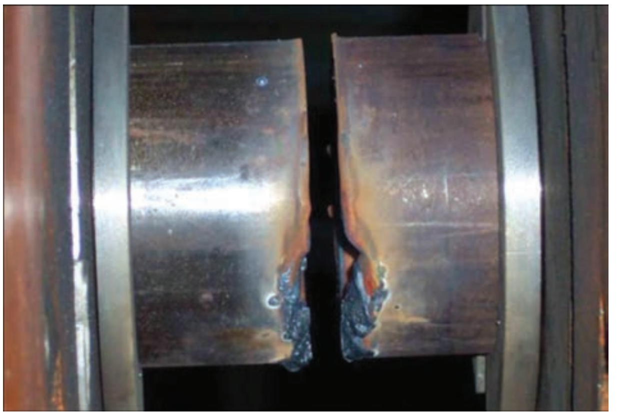

Figure 6. Molten metal crater

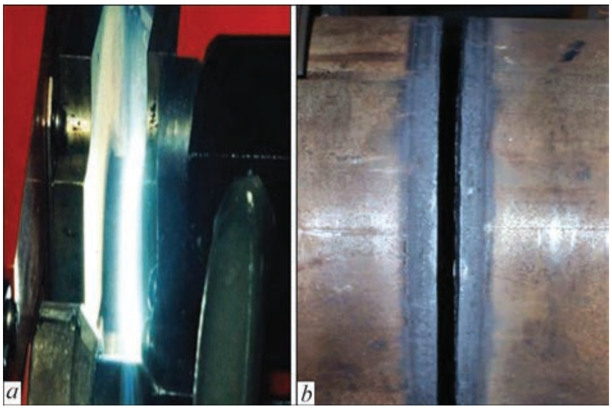

Figure 7. Pipe welding process, where: *a* — MIAB welding; *b* — pipe butts after heating

pipes (Figure 8, *a*). As the temperature of the ends increases, the thickness of the melt increases (Figure 8, *b*), which is held on the surface of the ends by surface tension forces. When a certain thickness is reached, the melt, under the influence of forces, rotates the arc along the heated ends (Figure 8, *c*), and begins to move in the same direction. The regulated speed of this movement under certain conditions can reach V_m = 3 m/s. The movement of the melt is due to the action of electrodynamic forces and the gas pressure in the arc gap formed by the arc column. This movement contributes to the stirring of the molten metal layer. Before upseting, the melt layer is evenly distributed along the perimeter of the pipe and the thickness of its butts (Figure 8, *d*).

In the initial period of upset, the gap between the butts decreases, and the arc discharge stops at the time of closing the gap (Figure 8, *e*), a continuous layer of molten metal begins to form between the butts (Figure 8, *f*), which, under the action of the magnetic field (current supply through the ends does not stop), continues to move in circular trajectories. This contributes to the renewal of the melt and the formation of a continuous layer over the entire cross-section of the pipes being welded. At the moment of closing the gap, the melt is squeezed out of the joint, and deformation of the heated metal layers in the solid state occurs [19].

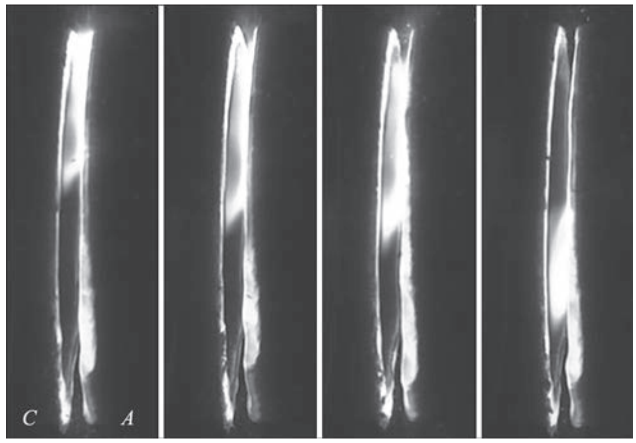

Figure 9. Movement of the cathodic and anodic plasma flow of the arc column

The magnitude and direction of the CMF induction have a great influence on the nature of the shift of the active spots of the welding arc. It was found that in the process of welding under the action of an external magnetic field, the arc speed during heating reaches V_a = 120–140 m/s depending on the diameter of the pipes, while initially the cathode plasma flow of the arc column is displaced relative to the anode (Figure 9). Having reached the anode, the cathode plasma flow of the arc forms a new anode spot. A movement of both the anode and cathode active spots of the arc is observed.

In order to study the nature of changes in the linear velocity of the arc, a series of experiments were conducted on welding pipes Ø121×8 mm, during which

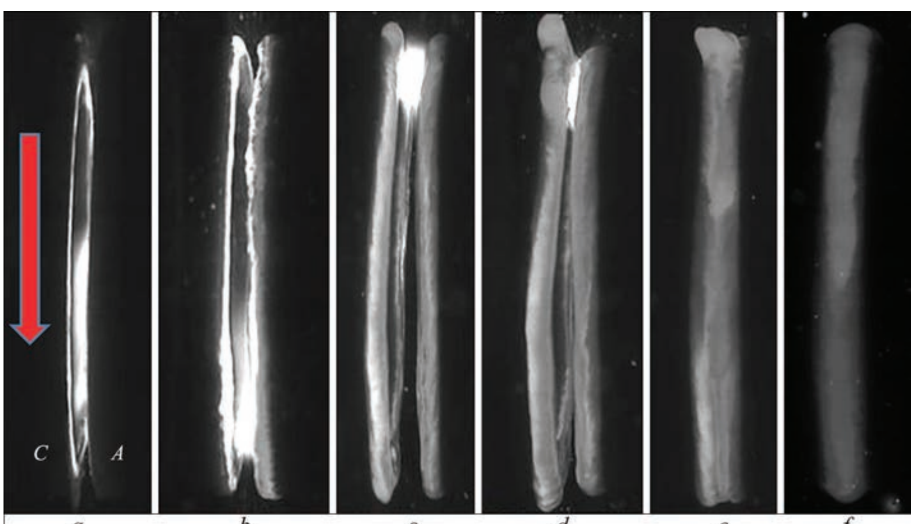

Figure 8. Stages of pipe welding, where: *a* — the beginning of arc movement under the action of the CMF; *b* — the formation of a layer of melt on the ends of the pipes; *c* — the movement of the melt during the heating process; *d* — the renewal of the melt before upset; *e* — the beginning of upset; *f* — the formation of a welded joint

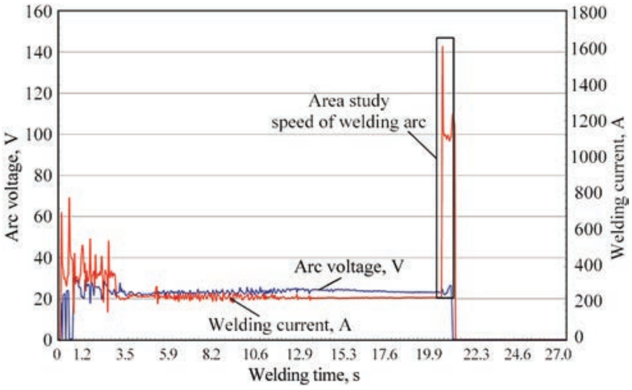

Figure 10. Main parameters of the pipe welding process

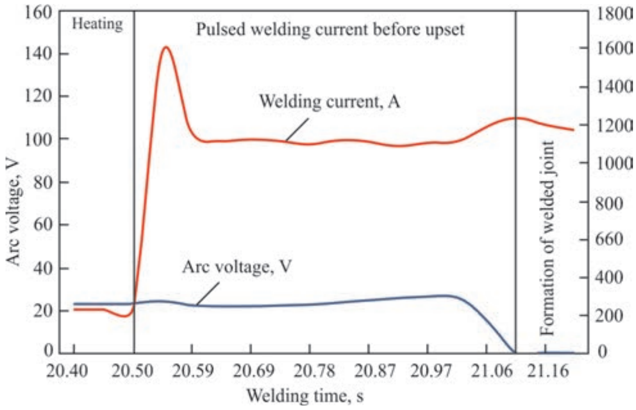

Figure 11. Welding arc current pulse before pipe upset

the technological parameters of the process were varied. In particular, the pulse of the welding current before the upset stage was varied within wide limits. Figure 10 shows a graphic record of changes in the main heating parameters. The rectangle on the graph highlights a section covering the period from the moment of the start of the pulsed increase in the welding current to the start of the upset under current. This section is presented in more detail in Figure 11, which made it possible to analyze the shape of the pulse and the nature of changes in the welding current both before the upset and directly during its execution.

When the welding arc current increases, the arc travel speed sharply accelerates (up to 240 m/s), which leads to intensive renewal of the welding surfaces and creates a protective environment. Experiments have shown that the magnitude of the pulse current before the upset should be higher than the heating current. A relatively uniform layer of liquid metal with a thickness of up to $\delta_{lm} = 0.5$ mm remains on the melted ends, which contributes to the formation of welded joints. The optimal pulse current has been established for each pipe size up to Ø200 mm. Changes in the pulse current by ±5 % from the optimal do not significantly affect the quality of the joints. The duration of the current pulse is within $t = 0.2$–0.6 s. At smaller ($t < 0.2$ s) values of the current pulse duration, the moving arc does not have time to completely renew the layer of molten metal saturated with gases from the end surfaces. In this case, the quality of the welded joints is low. Maintaining an increased current value for more than $t = 0.7$ s leads to increased consumption of heated metal of the pipe ends and a decrease in the quality of the welded joint. The upset is determined by the speed of closing the arc gap between the welded pipe ends and the formation of the welded joint. This ensuring conditions under which the liquid metal layer is preserved on the ends and controlled deformation of the HAZ occurs according to the specified allowance. The time of crystallization of the metal layer on the ends depends on many factors that accompany cooling. For pipes it ranges within $t = 0.01$–0.025 s. Interruptions of the current at the final stages of the heating process before upset lead to oxidation of the ends and crystallization of the liquid layer on the pipe ends.

It was experimentally determined that at upset rates less than $V_{upset} = 40$ mm/s, oxides are observed in weld-

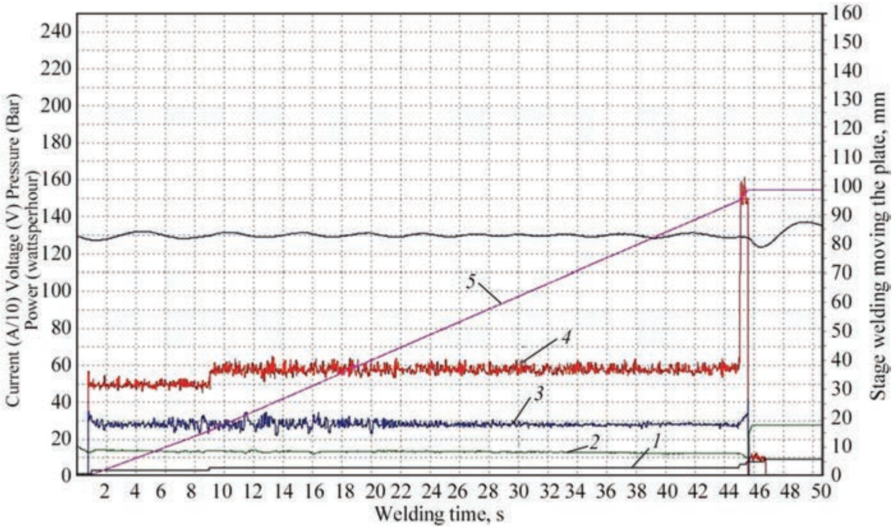

Figure 12. Diagram of the pipe welding process, where: *1* — position of the moving part of the machine; *2* — area of controlled upset; *3* — arc voltage; *4* — welding current; *5* — energy accumulated during the pipe heating process

ed joints, which significantly reduces the ductility of the joints and the strength properties of the joints.

The given scope of work allowed drawing the following conclusions:

Maintaining the setting and electrical parameters of welding within the permissible values leads to producing high-quality welded joints.

Defects along the joint line (oxides and matte spots) up to 2 mm^2 in size belong to defects of the base metal that fall into the joint. As tests have shown, these defects do not affect the qualing of welded joints.

MIAB WELDING TECHNOLOGY WITH PULSED HEATING AND CONTROLLED UPSET FOR FORMING WELDED PIPES JOINT

In the process of welding pipes, for example Ø140×8 mm, the system allows you to get a graphical representation of the process, which makes it possible to visually assessing the progress of the welding process, Figure 12. The welding current can be divided into three stages, and the welding time — into four stages. For welding pipes, the current I1 is used for approximately t_1 = 0.5 s, during which the welding pipes are briefly compressed to a short circuit and the welding rectifier is turned on. t_2 is the time period during which the short-circuited pipe ends are taken to the arc gap, after which an arc is excited between them. At the time stage t_2, the arc begins to rotate in the gap and heat the pipe ends, the arc current I_2 = 490–510 A. At the time stage t_3, the welding current increases to I_3 = 580–600 A, heating of the pipe ends the continues. At time stage t_4, the arc current pulse-like increases to I_4 = 1500 A, the arc accelerates and rotates at a relatively high speed, renewing the surfaces of the heated pipe ends. The welding cycle is completed with a controlled upset with an allowance S = 6.2 mm. The total time of welding of pipes Ø140×8 mm is t = 46 s.

The formation of welded pipe joints in MIAB welding, as in other press butt welding methods, occurs as a result of the joint deformation of the end surfaces of the pipes heated to a ductile state. Uniform heating of the ends is a necessary, but not sufficient condition for the formation of a high-quality joint. One of the key parameters affecting the quality of the joint is the arc rotation speed and the duration of heating. Too low rotation speed leads to an uneven thermal field, the formation of local zones of overheating or, conversely, underheating, which negatively affects the structure of the weld. Optimization of this parameter allows ensuring the stability of the process, uniform temperature distribution along the welding zone and reducing the probability of internal defects. The quality of the welded joint can be ensured even without the use of gas shielding, provided that the arc rotation speed at the moment before the upset is sufficient for constant renewal of the melt layer on the entire surface of the ends. This prevents crystallization of the metal in the time intervals between the passage of the arc through

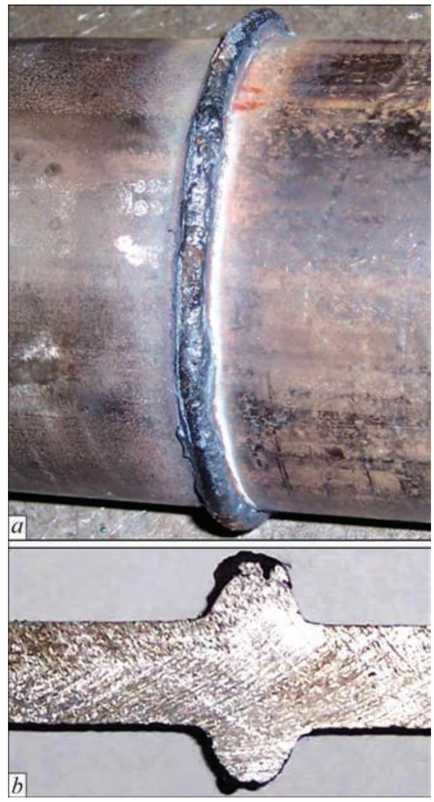

Figure 13. Formation of a welded pipe joint without an upset allowance, where: *a* — welded joint; *b* — cross-section of the welded joint

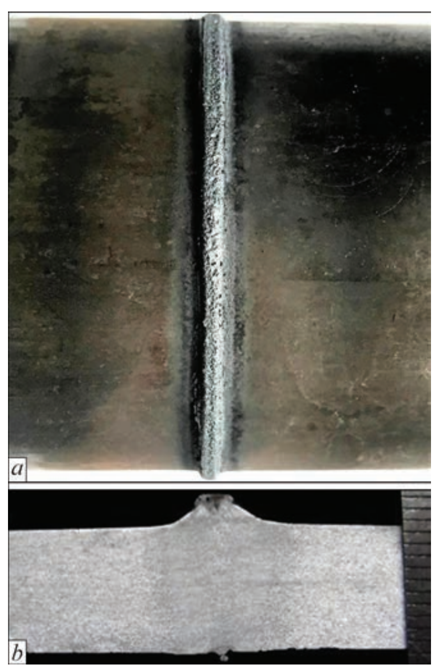

Figure 14. Formation of a welded joint with a controlled upset, where: *a* — welded joint; *b* — cross-section of the welded joint

Table 3. Basic technological parameters for welding

Steel grade	Pipe size, mm	Welding time, s	Upset force, kN	Pipe shortening, mm
09G2S	42/4	14	40.6	3.6
JIS STPG410	60.5/5.5	19	80	4.8
St35	76/16	82	255	12.4
DIN 17100 St52-3	90/5	16	135	4.8
ASTM A615 Grade 520	121/7	27	200	6.7
ASTM A615 Grade 520	121/10	43	278	9.2
API X70	168/7	31	247	6.8
API X70	219/8	38	281	7.7
ASTM A106 API 5L	114.3/6	19	140	5.7
ASTM A106 API 5L	148.3/6	28	171	5.6

Table 4. Mechanical properties of welded pipe joints

Steel grade	Pipe size, mm	σ_t, MPa		KCV_{+20}, J/cm^2		KCV_{-20}, J/cm^2		KCV_{-40}, J/cm^2
		Base metal	Welded joint	Base metal	Welded joint	Base metal	Welded joint	Welded joint
09G2S	42/5	469±10	465±14	56±5	68±10	58±3	69±5	–
JIS STPG410	60/5.5	458±10	456±10	94±4	87±3	96±3	91±4	92±3
St35	89/10	551±14	541±13	60±3	70±19	–	–	–
DIN 17100 St52-3	90/5	498±11	486±7	–	–	–	–	–
API X70	168.6/7.8	551±19	540±8	256±10	189±48	257±9	197±39	–
ASTM A615 Grade520	191/7	651±14	656±22	135±14	119±31	–	–	–
ASTM A106 API 5L	114.3/6	421±14	418±15	–	–	–	–	–
ASTM A106 API 5L	148.3/6	429±12	437±14	–	–	–	–	–

individual sections, which, in turn, contributes to the formation of a uniform and strong joint.

The formation of welded joints of pipes with a diameter of Ø140×8 mm, made without a controlled allowance for upset is shown in Figure 13, *a*. Figure 13, *b* shows a cross-section of the welded joint. The height of the external and internal reinforcement is up to 7 mm, which does not meet the requirements of API standards.

Controlling the pipe upset allowance after welding allows a significant reduction in the height of the welded joint reinforcement from 1.0 to 3 mm, depending on the pipe diameter, Figure 14.

Table 3 presents the main technological parameters for welding pipes with controlled upset.

Mechanical tests of pipe joints were carried out in accordance with the requirements of API [20] and DNV standards. The mechanical properties of welded pipe joints are shown in Table 4.

All joints of the specified pipes welded by the MIAB method without further heat treatment demonstrated impact toughness at test temperatures of +20,

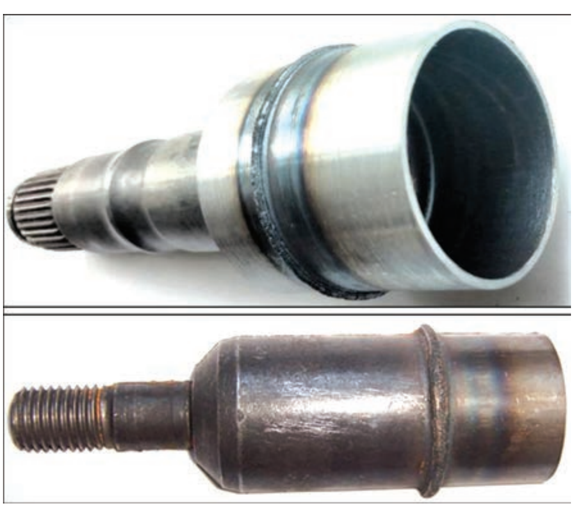

Figure 15. Parts of the automobile assortment

Figure 16. Welding pipes with fittings

Figure 17. Welding of pipelines for soil thermal stabilization systems, where: *a* — welded joints of the pipe with the bottom; *b* — system for soil thermal stabilization: building foundations; *c* — and oil and gas storage facilities

–20 and –40 °C at a level not lower than 80 % of the corresponding indices of the base metal.

Areas of application developed at PWI, Ukraine, MIAB welding technology & machine:

● automotive industry — welding of automobile shafts for various purposes (Figure 15);

● hydraulic systems of construction machinery — welding of pipes with fittings (Figure 16);

● pipeline construction — welding of pipes for soil thermal stabilization systems (Figure 17).

TECHNICAL ADVANTAGES OF THE MIAB WELDING PROCESS FOR PIPES, PIPELINES AND AUTOMOTIVE INDUSTRIES

The process has a number of important technical advantages:

● relatively short welding time;

● high productivity, especially in mass production;

● no need in welding materials and shielding gases, which reduces the cost of the process and simplifies its organization;

● localized (concentrated) heating of the ends of welded pipes;

● minimal allowances for melting and upset;

● unpretentiousness to the cleanliness of the side and welded surfaces;

● no strict requirements for the accuracy of preliminary preparation of parts;

● insignificant metal spatter during the process;

● the ability to control and record the main technological parameters in real time.

INNOVATIVE SOLUTIONS AND COMPLIANCE WITH STANDARDS

The use of this process allows you to reduce the duration of welding by up to 70 % compared to traditional methods.

The use of technology with pulsed welding current increase and precision upset in MIAB welding installations provides:

● increased energy efficiency of the welding process;

● improved technological quality of welded joints;

● reduced cost of welding equipment;

● reduced peak loads on the electrical mains by 50–70 % compared to traditional methods.

In addition, the MIAB welding process meets the requirements of the API 1104 standard, which is widely used in pipeline welding in many countries around the world. This indicates its compliance with international requirements for the quality, reliability and safety of welded joints.

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CONFLICT OF INTEREST
The Authors declare no conflict of interest

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