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MAG-WELDING OF REPAIR STRUCTURES OF MAIN GAS PIPELINES

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Abstract. Investigations on the development of a basic technology of the shielded-gas mechanized arc welding of strengthening structural elements which are used in repair of main gas pipelines were carried out. It is shown that the advanced welding wires Sv08G2S, E71T-1, DW-50, DW-A55 are in compliance with the requirements for providing the necessary level of mechanical characteristics, impact toughness of weld metal, content of diffusive hydrogen in the deposited metal and can be recommended for application in the further testing of technology for repair of the operating pipelines under the field conditions. The carried out works resulted in the working out of documentation on the technology of mechanized arc welding in shielding gases in repair of main gas pipelines of Ukraine.

Keywords: main gas pipeline, repair, arc welding, welded joint, flux-cored wire, cold cracks, preheating, diffusive hydrogen.

Introduction

It is generally known that the mechanized arc welding in shielding gases leads to the increase in efficiency of welding operations as compared with the manual arc welding. Systems of the mechanized arc welding on pipelines, which were developed by the leading world companies (ESAB, Lincoln Electric, CRC), have been already applied for not less than 40 years. However, all these developments concern mainly conditions of welding in construction of main gas pipelines (MGP). Experience in mechanization of repair welding operations under the field conditions on main gas pipelines, subjected to internal pressure, is rather limited.

Thus, there is a need in intensification of repair-welding operations with a simultaneous improvement of their quality and safety. One of the variants for coming out from this situation is an application of the technology of mechanized arc welding in shielding gases using the advanced welding consumables.

Selection of welding consumables for the mechanized arc welding

To optimize the technology of the shielded-gas arc welding in all the spatial positions (overhead, horizontal in vertical plane, flat), the welding consumables which are in compliance with requirements [1–5] were selected: solid wire Sv08G2S (Ukraine); flux-cored wires DW-50, DW-A55 (Kobelco, Japan), E71T-1 (Baoding lanyu welding material, China) and PPs-TMV7 (“TM. Veltek”, Ukraine). This selection is grounded by the need in comparison of welding-technological characteristics of new, advanced high–quality flux-cored wires with the less expensive wire Sv08G2S, well-known and widely spread in industry by experience, to determine the feasibility of its further application under the conditions of pressure MGP repair. All wires had a similar 1.2 mm diameter.

Mechanical properties of metal of butt and overlap-butt welds

In repair of damaged regions of MGP the bands and couplings of different designs are used. They strengthen the pipe wall, and also save the serviceability of the main pipeline during violation of the wall integrity in site of the defect under the coupling. To join separate cylindrical elements between themselves, as well as with pipeline, the longitudinal butt and circumferential overlap–butt welds are applied.

Standard technical documentation [6] has the requirements for welding consumables, which are used for MGP of external diameter up to 1420 mm, made of steels of up to K60 class of strength inclusively and which are operating at pressure of up to 8.3 MPa, to be in compliance with the following conditions:

– temporary fracture resistance at static tensile test should be not lower than the standard temporary fracture resistance of the pipe base metal;

– hardness of weld metal should not be higher than 280 *HV*10, heat-affected zone (HAZ) of not more than 300 *HV*10 for pipes of up to K55, class of strength inclusively and not higher than 325 *HV*10 for pipes of strength class higher than K55 to K60 inclusively;

– impact toughness of weld metal should be not less than 34 J/cm^2 (by Charpy) at temperature by 20 °C lower than the minimum temperature of the pipe wall of gas pipeline in service (for the conditions of gas transport system of Ukraine this temperature may be considered as 0 °C).

To determine the mechanical properties of welded joints, the butts of 15.7 mm thickness were welded at 60° beveled edges. Each layer was made for one pass (Fig. 1, *a*) The material was pipe steel of X70 class of strength with mechanical characteristics σ_Y>480MPa, σ_t>560MPa, δ_5>18 %.

Welding was performed by the combined technology [11]. A root weld of the butt joint was performed by the manual method with 3 mm diameter rod electrode (UONI 13/45), a groove was filled with wires. Shielding gases were CO_2 and mixture (82 %)+CO_2(18 %). Welding conditions were as follows: Sv08G2S – I_w=140-150A, U=20…21V; flux-cored wires – I_w=200-220A, U=25…27V. Welding speed was v_w=0.2-0.25 m/min, $Q_{g.}$=15 l/min. Specimens for determination of mechanical characteristics of weld metal and impact toughness were cut out according to the requirements [3, 5]. Results of tests are given in Table 1.

Table 1

Mechanical properties of weld metal

Welding material, shielding gas	σ_Y, MPa	σ_t, MPa	δ_5, %	ψ, %	Impact toughness $a_\text{н}$, J/cm^2 at temperature, °C		
					0	-20	-40
Sv08G2S, CO_2	423	552	27.4	72.1	$\frac{168-138}{153}$	$\frac{91-88}{89}$	$\frac{71-62}{67}$
Sv08G2S, Ar+CO_2	430	561	30.9	75.1	$\frac{177-154}{165}$	$\frac{98-93}{95}$	$\frac{75-71}{72}$
E71T-1, Ar+CO_2	444	557	29.0	71.6	$\frac{151-107}{128}$	$\frac{55-53}{53}$	$\frac{63-32}{46}$
DW-A55, Ar+CO_2	484	589	27.3	71.0	$\frac{176-152}{164}$	$\frac{147-128}{136}$	$\frac{49-45}{46}$
DW-50, CO_2	468	567	29.1	72.8	$\frac{44-40}{41}$	$\frac{23-22}{22}$	$\frac{14-13}{13}$
PPs-TMV7, CO_2	476	570	29.0	71.6	$\frac{172-170}{170}$	$\frac{125-110}{117}$	$\frac{86-80}{83}$

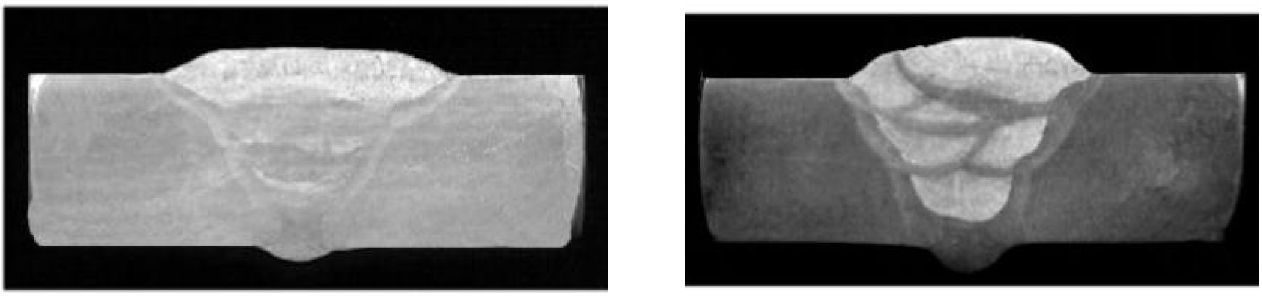
The analysis of obtained results and their comparison between themselves showed that concerning the fulfillment of the first requirement the wires E71T-1, DW-50, PPs-TMV7 and Sv08G2S can be applied for welding steels of K55 class strength (X56, X60), and flux-cored wire DW-A55 can be applied for welding pipes of K60 (X70) class of strength. Measurement of metal hardness in the weld center and HAZ showed that all the grades of wires are in compliance with the second condition (Table 2).

Table 2

Mean hardness of weld metal and HAZ(*HV*10)

Welding material, shielding gas	Sv08G2S, CO_2	Sv08G2S, $Ar+CO_2$	E71T-1, $Ar+CO_2$	DW-A55, $Ar+CO_2$	DW-50, CO_2	PPs-TMV7, CO_2
Weld metal	149	148	148	153	149	148
HAZ	162	160	154	158	165	155

As to the values of impact toughness (KCV) it was found that the flux-cored DW-50 did not correspond to the third requirement at test temperatures -20 and -40 °C (see Table 1). Assumption was made that the cause of low values of impact toughness at wire DW-50 is connected with welding technique, as the process of filling the groove was performed with transverse oscillations across the entire width of the butt groove at high values of specific heat input [7]. Therefore, the decision was taken to replace the scheme of the groove filling by such one, where the butt welding was performed by stringer beads without transverse oscillations (Fig. 1, b) at moderate heat input. Results of testing the specimens of weld metal, welded by using the new scheme showed the significant increase in mechanical characteristics and impact toughness (Table 3).



a *b*

***Fig. 1.** Welded butt joint:*
a – welding by the "one layer per one pass" method; b – welding with stringer beads

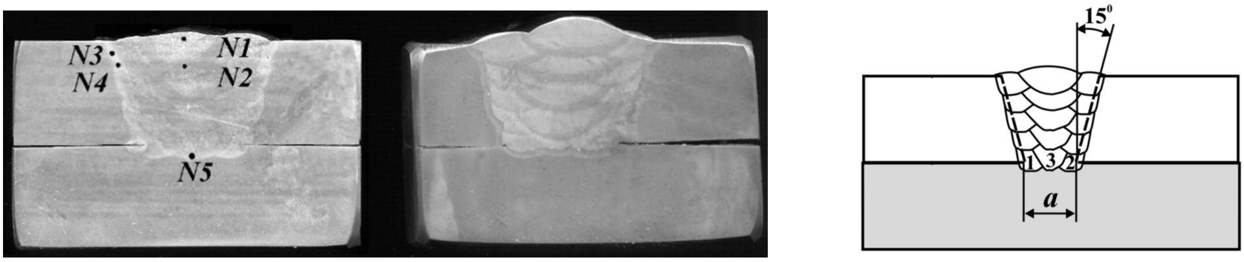
Table 3

Mechanical characteristics and impact toughness of weld metal

Welding material, shielding gas	σ_Y, MPa	σ_t, MPa	δ_5, %	ψ, %	Impact toughness $a_н$, J/cm^2 at temperature, °C		
					0	-20	-40
DW-50, CO_2	540	612	27	71.5	$\frac{217-172}{197}$	$\frac{160-101}{125}$	$\frac{87-51}{70}$

Comparison of these results with previous ones showed that to increase the mechanical properties and impact toughness of welded joint metal it is necessary to replace the previously selected technique of butt welding by such one that applies the filling of groove by stringer beads without oscillations. This conclusion was confirmed in evaluating the impact toughness of the overlap–butt joints, in which each layer was made by separate beads *1, 2* at angle on each edge, then the bead *3* was made in the middle (Fig. 2, *c*). During welding the wires PPs-TMV7 and Sv08G2S were used.

The results of specimens testing on impact toughness are given in Table 4. The analysis of data showed that the high level of impact toughness is remained in the whole range of test temperatures, which much exceeds the minimum required level of this value, i.e. not lower than 34 J/cm^2.



a *b* *c*

Fig. 2. *Overlap-butt welded joint: a – macrosection of joint using Sv08G2S; b – macrosection of joint using PPs-TMV7; c – scheme of edges filling and welding (N1…N5 are the regions of metallographic examinations; a is the gap between the coupling elements)*

Table 4

Impact toughness (KCV) of metal of overlap-butt welds

Welding material, shielding gas	Impact toughness, $a_{н}$, J/cm^2 at temperature °C		
	0	-20	-40
Sv08G2S, CO_2	$\frac{164-148}{155}$	$\frac{171-125}{142}$	$\frac{100-65}{81}$
PPs-TMV7, CO_2	$\frac{176-153}{165}$	$\frac{160-127}{140}$	$\frac{127-105}{118}$

For metallographic examinations were selected the following regions were selected: *N1* –weld metal of previous layer; *N2* – HAZ in weld metal; *N3* – zone of coarse grain of previous layer; *N4* – zone of coarse grain with structural changes after making the next layer; *N5* – zone of coarse grain in weld root.

Investigation of joint specimens showed that in regions *N1*, *N2* the structure is ferrite-pearlite with a ferrite phase domination. Hardness is 1650…1750 MPa at *HV*1. In region *N2* the structure of metal is fine-dispersed ferrite-pearlite with 10 grain number due to heat effect. In the heat-affected zone (regions *N3*, *N4*) the structure is ferrite-pearlite with hardness 1970…2130 MPa. In region *N5* the increase in hardness up to 2360…2640 MPa is observed due to cooling increase. It was found that welding with separate beads allows producing the fine-grain almost homogeneous ferrite-pearlite structure in joint height and this favors the solution of task of obtaining the increased values of impact toughness in welds as compared with the required minimum ones.

Evaluation of welded joint resistance to the cold crack formation

One of the factors of cold crack initiation is a stress-strain state of the welded joint [8, 9]. In repair of pipes with local corrosion defects the designs “patch-coupling” or “patch-coupling with sealing material“ are used [10]. These designs are featured by the presence of a circumferential overlap-butt weld, by which the patch of 100…120 mm diameter is welded around the contour with the coupling and pipe. Using this technical solution a high level of stresses is observed in the multilayer weld due to shrinkage of weld metal and rigid fastening. Together with other factors (diffusive hydrogen, microstructure) there is a risk of cold cracking.

To define the conditions which influence on the resistance against cold crack formation in the “patch-coupling” overlap-butt joint, the tests were carried out using the sample “Marine” [11, 12]. This technological sample (Fig. 3) simulates completely a real weld, and at a proper ratio of the disc diameter to plate width it can provide the level of stresses close to the steel yield strength.

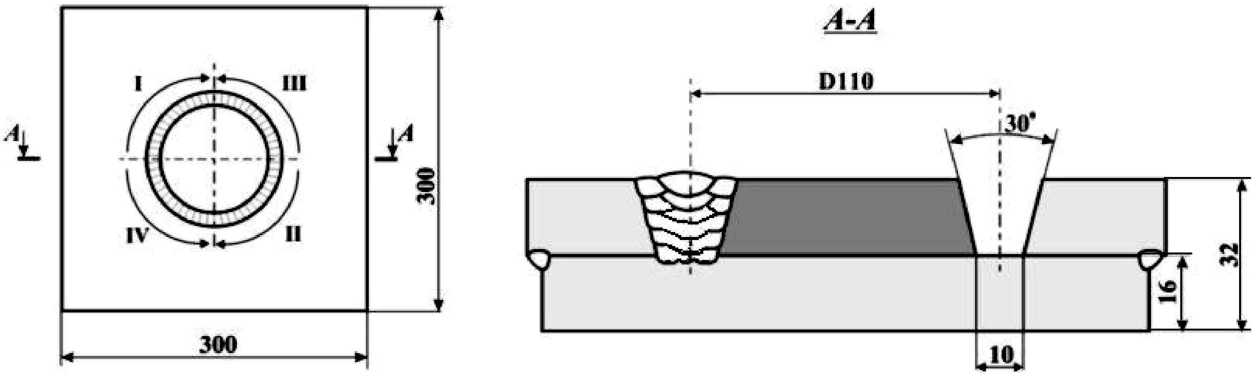
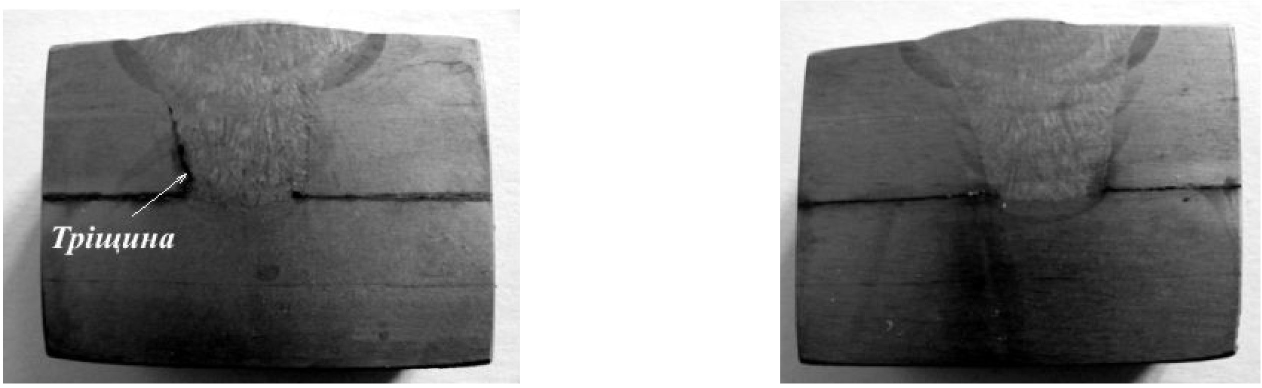


Fig. 3. *Scheme of technological sample "Marine" with a sequence of the overlap-butt joint welding*

The parts of two samples were manufactured of pipe segments of 1420 mm diameter. CO_2 welding was performed with the flux-cored wire PPs-TMV7 according to the scheme. Welding conditions were as follows: I_w=190…200 A, U=26-27 V, $v_{wire.}$=9.1 m/min. Two sections were cut from each quadrant for the visual control of cracks. It was expected that the highest level of stresses would be occurred in the quadrant IV, where the crack had to be initiated [13].

Examination of sections of the sample, which was not subjected to preheating, showed that the laying out of next bead after cooling the previous one to 20 °C led to the formation of cold cracks in the quadrant IV(Fig. 4, *a*). Using preheating and concurrent heating up to 160–180 °C temperature allowed preventing their initiation (Fig. 4, *b*).



a *b*

Fig. 4. *Sections of sample "Marine" in mechanized welding:*
a – without preheating; b – with preheating and concurrent heating up to 160–180 °C

It was found that in the first case the crack initiated in metal of the weld root part at the fusion line on the external side of the circular weld. The crack initiation is beginning at the stress concentrator, i.e. zone of transition of surfaces of the sample cover elements into the weld metal. This defect can be caused by radial stresses from metal shrinkage, which are higher on the weld external side than those on the internal side [14]. In this connection, to prevent the occurrence of cold cracks in the multilayer welds it is rational to apply preheating before welding up to 160…180 °C and keeping this temperature before each next pass, as well as to use the quality welding materials with a level of ductility δ_5>20 % at temperature -20 °C, and which guarantee the level of the diffusive hydrogen in the deposited metal of not more than 10 cm^3/100 g. To decrease the level of stresses it is necessary additionally to increase the diameter of patches up to 200 mm.

The other factor which greatly influences the risk of cold crack formation during the mechanized arc welding on in-service MGP is a microstructure of the welded joint HAZ. It was found by calculations and experimentally that during welding without preheating the cooling rate of weld metal and HAZ within the 800…500 °C temperature range at intensive heat removal is 45…60 °C/s, and in applying of preheating up to150 °C it is 30…40 °C/s. As the majority of pipe steel grades are prone to formation of hardened structures under the mentioned conditions, the investigations were made for study of effect of metal cooling rate on HAZ structure of steel X70.

The investigations were carried out by using the complex Gleebel 3800. Using special specimens the thermal cycle of welding was simulated on the HAZ overheating region, where the cooling rate within 800…500 °C range was 40, 50, 60 and 90 °C/s. The diagram of transformation of overcooled austenite was obtained (Fig. 5) and its analysis showed the following.

Within the ranges of cooling rates 40…60 °C/c the amount of martensite phase in steel X70 is increased from 8.6 % up to 23 %, and this is much lower than 50 %, at which steel, as considered, prone to the cold crack formation. The increase in cooling to 90 °C/s, characteristic for the wet underwater welding conditions, increases the amount of martensite in HAZ up to 65…68 %, which is hazardous for the welded joint serviceability.

Metallographic examinations showed that for cooling rates 40…60 °C/s the integral hardness in HAZ is within the ranges of 270…300 *HV*10 and this does not exceed the threshold in 325 *HV*10 for steels of X70 class of strength, and the applying of preheating up to 150 °C has a positive influence on the HAZ microstructure morphology.

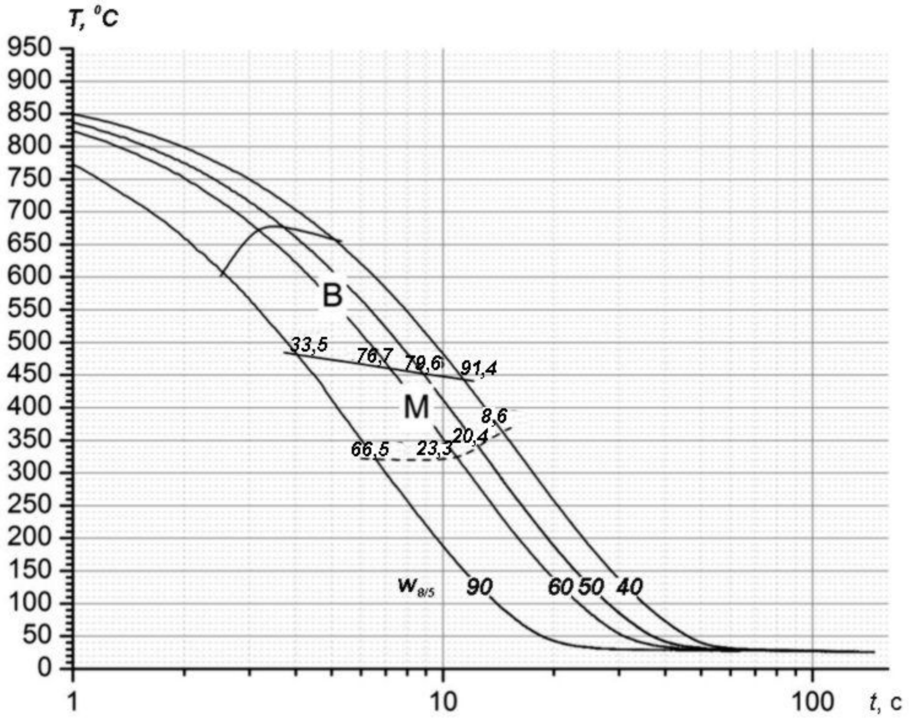


Fig. 5. *Diagram of transformation of overcooled austenite in HAZ of steel X70 at different cooling rates in the range of 800…500 °C: 1) 40 °C/s; 2) 50 °C/s; 3) 60 °C/s; 4) 90 °C/s*

As is known, the diffusive hydrogen, one of sources of which is electrode metal, has a great influence on the hazard of cold crack initiation in welded joints. The standard-technical documentation regulates the application of welding consumables which guarantee the content of the diffusive hydrogen in the deposited metal of not more than cm^3/100 g [15]. In this connection, all the welding wires were investigated for determination of the diffusive hydrogen content in the deposited metal $[H]_{diff.\ d.m.}$ using the chromatographic method [16]. Before starting the experimental works the flux-cored wires were dried in furnace at 200…250 °C temperature for not less than 3 hours for the moisture removal. The metal deposition on special specimens (3 pieces for each wire) was performed in mixture $Ar+CO_2$ by using the welding tractor TC-17 at the conditions which provided the energy input at the level of 5.8…6.2 kJ/cm. Results of gas analysis and calculations of $[H]_{diff.\ d.m.}$ for each grade of wire are given in Table 5

Table 5

Mean content of $[H]_{diff.d.m.}$ in deposited metal, cm^3/100 g

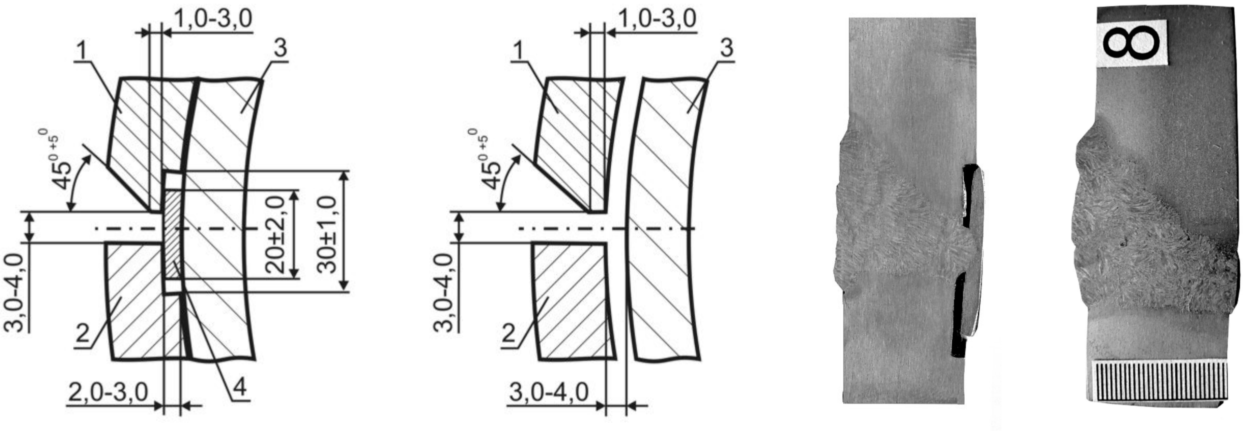
Sv08G2S	DW-50	DW-A55	E71-T	PPs-TMV7
3.4…3.6	7.0…8.2	7.6…8.5	9.7…10.0	10.…11.8

It is seen that the least content of the diffusive hydrogen is observed in the deposited metal when applying the conventional solid wire SV08G2S and this corresponds to the welding consumables which provide the very low level, i.e. to 5 cm^3/100 g. Flux-cored wires DW-50, DW-A55 i E71-T are in compliance with welding consumables which provide the low level of diffusive hydrogen, i.e. to 10 cm^3/100 g. Wire PPs-TMV7 exceeds the allowable threshold in 10 cm^3/100 g and cannot be recommended for application under the conditions of MGP repair.

Development of technology for welding of strengthening structural elements

In the development of the technology of mechanized arc welding in shielding gases of strengthening structural elements the main attention was paid to optimizing the technique of welding of butt and overlap-butt joint in different spatial positions. In this case the efforts were directed to determine such welding conditions which, on the one side, could provide the quality formation of multilayer welds, and, on the other side, did not require radical corrections during changing the spatial position.

Welding of long butt joints in horizontal position in vertical plane (Fig. 6, *a*, *b*) was performed by wires DW-A55 and Sv08G2S in mixture of $Ar+CO_2$. Material was segments of pipe X70 of 1429 mm diameter and 16 mm wall thickness.



a *b* *c* *d*

***Fig. 6.** Longitudinal butt joints of strengthening structural elements:*
a – edge preparation for welding with a backing plate; b – edge preparation for welding without any backings;
c – macrosection of joint with a backing plate (wire DW-A55);
d – macrosection of joint made by wire Sv08G2S without any backings:
1 – wall of upper strengthening element; 2 – walls of bottom strengthening element;
3 – wall of gas pipeline; 4 – backing plate

The flux-cored wire was used for the variant of welding with a baking plate (Fig. 6, *c*), wire Sv08G2S was also for welding without any backings (Fig. 6, *d*). The technique of welding had to lay out of separate passes with stringer beads with small transverse oscillations. The root pass was made at the torch inclination by a backward angle. The second and next filling passes were made without transverse oscillations by narrow beads at the torch inclination by a forward angle, correcting the number of passes in each layer depending on the edge preparation width. The finishing layer was made with separate passes at small transverse oscillation to provide a smooth transition to the base metal. Welding conditions are given in Tables 6, 7.

Table 6

Recommended conditions of butt joint welding with wire DW-A55

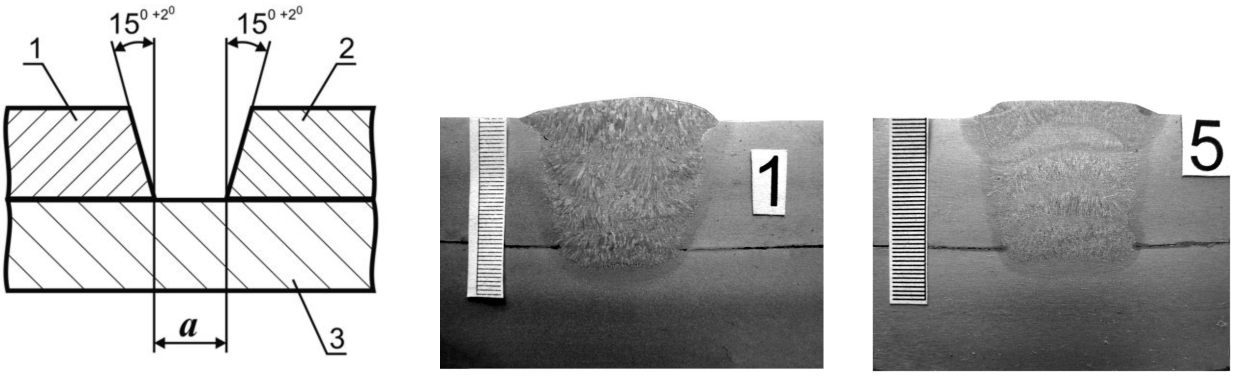
Parameter	Pass in groove filling		
	Root	Filling	Finishing
Wire feed speed, m/min	9.0…9.2	9.0…9.2	7.4…7.7
Welding current, A	200…210	205…215	180…190
Arc voltage, V	26.…26.3	26.5…27.0	25.0…26.0
Wire stickout, mm	20…23	16…20	10…14
Shielding gas	Ar (82 %)+CO_2 (18 %)		

Table 7

Recommended conditions of butt joint welding with wire Sv08G2S

Parameter	Pass in groove filling		
	Root	Filling	Finishing
Wire feed speed, m/min	3.6…3.8	4.0…4.1	3.6…3.8
Welding current, A	125…130	145…155	125…130
Arc voltage, V	18.0…18.5	19.0…20.0	18.0…18.5
Wire stickout mm	18…23	16…20	10…14
Shielding gas	Ar (82 %)+CO_2 (18 %)		

The technology of producing multilayer circumferential overlap-butt joints consists in performance of the welding process in upward direction by sectors. At edge groove width ***a*** ≥15 mm (Fig. 7, *a*) all the layers should be made by the "one layer for two passes" method. This gives an opportunity to increase the values of weld impact toughness. At edge groove width ***a***<15 мм the first layer should made by the "one layer for one pass" method, and starting from the second layer the welding should made by the "one layer for two passes" method (Fig. 7, *b*, *c*). The finishing layer of the overlap-butt joint should be made by the "layer for one pass" or "layer for two passes" depending on value ***a***. The total number of layers in the overlap-butt joints is determined by the wall thickness of strengthening structural elements.



a *b* *c*

Fig. 7. *Overlap-butt joints of strengthening structural elements: a – edge preparation for welding; b – macrosection of joint made with wire DW-A55; c – macrosection of joint made with wire Sv08G2S: 1 – wall of strengthening element (coupling); 2 – wall of strengthening element (technological ring); 3 – wall of pipeline*

To guarantee the fusion of edges with pipeline the welding in the overhead position should performed in “backward“ position of electrode. Conditions of welding are given in Tables 8 and 9.

Table 8

Recommended conditions of overlap-butt joint welding with wire DW-A55

Parameter	Pass in groove filling	
	Filling	Finishing
Wire feed speed, m/min	8.0…9.1	7.4…8.0
Welding current, A	190…220	180…200
Arc voltage, V	26.5…27.0	26.0…26.5
Wire stickout, mm	12…23	10…16
Shielding gas	Ar (82 %)+CO_2(18 %)	

Table 9

Recommended conditions of overlap-butt joint welding with wire Sv08G2S

Parameter	Pass in groove filling	
	Filling	Finishing
Wire feed speed, m/min	4.0…4.1	3.7…3.8
Welding current, A	135…140	125…130
Arc voltage, V	19.5…20.5	18.0…18.5
Wire stickout, mm	12…23	10…16
Shielding gas	Ar (82 %)+CO_2(18 %)	

Conclusions

The carried out investigations demonstrated that application of mechanized arc welding in shielding gases by using the traditional (Sv08G2S) and advanced welding consumables (DW-50, DW-A55, E71-T) allowed reaching the requirements specified for service characteristics of repaired regions of the main gas pipelines. The carried out works resulted in the working out of documentation on the technology of mechanized arc welding in shielding gases in repair of main gas pipelines of Ukraine.

References

[1] GOST 2246-70: Steel welding wire. Technical Specifications. – App. 01.01.1973. – FGUP "Standartinform”, 2008. – 19 p.

[2] AWS A5.18: Carbon Steel Electrodes and Rods for Gas Shielded Arc Welding // American Welding Society, Miami, 2005.

[3] AWS A5.28: Specification for Low-Alloy Electrodes and Rods for Gas Shielded Arc Welding // American Welding Society, Miami, 2005.

[4] GOST 26271-84: Flux-cored wire for arc welding of carbon and low-alloy steels. General Technical Specifications – App. 01.01.1987. – M.: Gosstandart of USSR, 1987. – 19 p.

[5] AWS A5.36: Specification for Carbon and Low-Alloy Steel Flux Cored Electrodes for Flux Cored Arc Welding and Metal Cored Electrodes for Gas Metal Arc Welding // American Welding Society, Miami, 2012.

[6] STO Gasprom 2-2.2-136-2007: Instruction on technologies of welding in construction and repair of industrial and main gas pipelines. Part 1. Technology of welding in repair of in-service industrial and main gas pipelines. – App. 22.09.2007 – OJSC “Gasprom” – 2007.

[7] Handbook on welding. All-position flux-cored wires for non-alloy and low-alloy steels. – ESAB. – 32 p.

[8] Makarov E. L. Cold cracks in welding of alloy steels / E. L. Makarov. – M.: Mashinostroenie, 1981. – 247 p.

[9] Makhnenko V. I. Safe service life of welded joints and elements of advanced structures / V. I. Makhnenko. – K.: Naukova Dumka, 2006. – 618 p.

[10] GBN B.3.1-00013741-12:2011: Main gas pipelines. Repair by arc welding under service conditions. – App. 06.09.2011. – K.: Ministry of Energy and Coal Industry of Ukraine. – 2011. – 152 p.

[11] Testing of metals / Collection of articles. Ed. By K. Nitsshe. – M.: Metallurgy, 1967. – 452 p.

[12] Boot V. S., Maksimov S. Yu. Oleinik O. I. Susceptibility to cracking of welded joints of repaired structures on main gas pipelines // Avtomaticheskaya Svarka– 2014. – No. 11. – P. 17–26.

[13] Bekker M. V. Repair of main pressure pipelines / M. V. Bekker, V. S. Boot, R. M. Govdyak, et al. – K.: Kiev, 2008. – 239 p.

[14] Nikolaev G. A. Welded structures. Strength of welded joints and deformation of structures / G. A, Nikolaev, S. A. Kurkin, V. A. Vinokurov. – M.: Vysshaya shkola, 1982. – 272 p.

[15] Pokhodnya I. K. Metallurgy of arc welding. Interaction of metal with gases / I. K. Pokhodnya, I. R. Yavdoshchin, A. P. Paltsevich, V. I. Shvachko, A. S. Kotelchuk. – K.: Naukova Dumka, 2004. – 442 p.

[16] GOST 23338-91: Welding of metals. Methods of determination of diffusive hydrogen content in deposited metal and weld metal. – App. 01.07.1992. – M.: Gosstandart of USSR, 1991. – 20 p.