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TWO-WIRE SUBMERGED-ARC WELDING WITH COLD WIRE APPLICATION

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ABSTRACT

The possibility for improvement of welded joint properties by feeding cold wire into the weld pool to increase its cooling rate was considered. The technique of the process was investigated in the case of two-wire submerged-arc welding of low-alloyed 10G2FB steel at application of cold wire. Impact toughness of the metal of the weld and HAZ was determined on IX type specimens with a sharp notch to GOST 6996, depending on welding process parameters, and welded joint structures were studied.

KEY WORDS: low-alloyed steel, thermal cycle, impact toughness, cold wire, submerged-arc welding

INTRODUCTION

The problem of ensuring the reliability of the main gas pipelines by improving the properties of the welded joints remains to be urgent. One of the possible directions of its solution is a method proposed by ESAB Company, Sweden, for submerged-arc processes [1–3] with feeding cold wire (CW) into the weld pool. The idea of the method consists in increasing the welded joint cooling rate with the respective improvement of its structure and mechanical properties.

The objective of the research was evaluation of the effectiveness of the above-mentioned process in the case of two-wire submerged-arc welding in the modes characteristic for pipes of medium thickness (12–25 mm). In addition to mechanical properties of welded joints this process was to provide the specified penetration and sound formation of welds of 22–25 mm width with 0.5–3.0 mm reinforcement height and its smooth transition to base metal (BM).

When choosing the experimental parameters, the reference point was work [1], where the external weld of a two-sided butt joint 13 mm thick from X70 steel was welded by two arcs in the presence or absence of CW. Welding wire of 4 mm diameter of BA S2 Mo grade and BF 6.4 flux with 1.7 basicity were used.

BM chemical composition (wt.%) is given: 0.046 C; 1.76 Mn; 0.24 Si; 0.21 (V, Mo, Nb, Ti); 0.54 (Cu, Ni, Cr), as well as the composition of cold and electrode wires (wt.%): 0.10 C; 1.04 Mn; 0.1 Si; 0.56 Mo; 0.02 Ni; 0.03 Cr; 0.03 Cu.

The relatively high carbon content in the welding wire was supposed to lower austenite transformation temperature, so as to increase the acicular ferrite fraction and improve the weld structure, respectively.

Welding process parameters according to [1] were as follows:

- arc 1 — 1040/30, reverse polarity direct current;
- arc 2 — 830/34, square wave alternating current;
- welding speed — 160 cm/min (96 m/h);
- CW feed rate — 25.4 cm/min (15.2 m/h).

By our data, for such a mode welding wire feed rate in arcs 1 and 2 is equal to 135–140 m/h, so that CW fraction relative to each of these wires should be equal to ~0.11. In our experiments this fraction was increased as far as it was allowed by weld formation quality to achieve maximum effectiveness of the process.

CW is placed ahead of the first arc, between the arcs or behind the last arc [2]. In work [1] CW was placed behind the last arc that seems to be optimal, as in this case the penetration depth is not decreased, and weld pool is cooled to the maximum.

In the above-mentioned work HAZ was tested for impact bending, using specimens of 5×10×55 mm size with a sharp notch, one half of which passed through the zone of coarse grain, and the second one - through the zone of fine grain. At temperatures of 20 °C and –30 °C CW application increased the impact energy of HAZ metal by 10 J, and at –45 °C — by 20 J. More essential results as to HAZ properties were obtained at testing by SENT procedure.

Owing to reduction of heat input by 9 % and increase of the cooling rate by 10 % the HAZ structure was improved by a number of characteristics:

- reduction of primary austenite grain sizes from 68 to 55 μm, as a result of shortening of the time of staying in the austenite temperature range of 1400–1100 °C;
- reduction of the fraction of coarse MAK-phase particles of more than 2 μm size from 3.2±0.2 to 1.0±0.1 %;
- reduction of the sizes of ferrite-bainite grain in the HAZ from 17.6±5.0 to 15.3±4.5 μm (for X70 steel the mentioned grain size was 4.1±0.5 μm);
- increase of the angles of grain disorientation.

Table 1. Process parameters and weld dimensions

Weld number	Arc number	$V_{CW f}$, mm/10 s	I_w/U_a, A/V	$V_{el f}$, mm/10 s	ψ	L_{cr}, mm	Weld dimensions, mm		
							h	*b*	*a*
600	1	105	1100/36	485	0.21	185	14.6–14.8	22.7–23.1	3.0–3.5
	2		1010/38	498					
601	1	70	1100/36	485	0.14	195	~15.0	23.9–24.9	2.6–2.8
	2		980/38	498					
602	1	0	1100/36	485	0	230	~15.0	24.0–25.0	2.4–2.6
	2		960/38	498					

Note. Welding speed of 65 m/h (I_w — welding current; U_a — arc voltage; $V_{CW f}$ — cold wire feed rate; $V_{el f}$ — electrode wire feed rate; I_w; U_a; $V_{CW f}$, $V_{el f}$; ψ — ratio of cold and electrode (on arc 2) wires; L_{cr} — crater length; *h*, *b* — penetration and weld width; *a* — its reinforcement height).

MATERIALS AND PROCEDURES

In our laboratory tests, plates of low-alloyed cold-resistant steel 10G2FB of 19 mm thickness were used as BM. Electrode and cold wire of Sv-08G1NMA grade of 4.0 mm diameter, as well as OP 132 flux, made in France, were applied. Power to the first and second electrodes was supplied from VSZh-1600 rectifier and laboratory transformer with a square waveform of current, respectively. The inclination of the first and second electrodes to the vertical was equal to –7° and 20°, and the distance between them was 20 mm. Welding was performed on V-shaped grooves of 5 mm × 90° size.

During work performance the influence of CW feed rate and its position on arcing stability and weld formation quality was determined with correction of the process parameters.

To evaluate the effectiveness of the new process in improvement of welded joint properties, comparative testing was performed with and without CW application. With this purpose, the specimens of weld and HAZ metal of IX type to GOST 6996 of 10×10×75 mm size were tested for impact bending at temperatures of –20 and –40 °C, and metallographic analysis of the joint structure was also performed.

In keeping with the international standard for manufacturing pipes for underwater gas pipelines [4] the mentioned specimens were selected from the weld upper part at 2 mm distance from BM surface.

In the HAZ test specimens the notch was made normal to BM surface through the middle of the fusion line (FL) so that one of its halves passed through the weld, and the other one — through the HAZ. With such a procedure a considerable part of the notch is in the coarse grain zone that impairs the impact toughness properties.

In the case of weld asymmetry, the notch was made from the side of a more round FL, avoiding artificial overestimation of the test results.

Analysis of welded joint microstructure was performed with application of optical microscope on microsections etched in 4 % solution of HNO_3.

RESULTS

TEST SERIES 1

CW was placed behind the last arc with backward inclination at 37° angle to the vertical so that in the state of shorting on BM the tips of CW and the last electrode contacted each other.

Two CW feed rates were tested, which were equal to 0.14 and 0.21 relative to the feed rate of second arc electrode wire (ψ coefficient) (Table 1). At increase of ψ coefficient to 0.21 weld formation became worse — its width was reduced from 24–25 to 23–22.7 mm, and reinforcement height increased from 2.4–2.8 to 3.0–3.5 mm (Figure 1).

CW closeness to arc 2 generated the self-regulation effect with increase of its current by approximate-

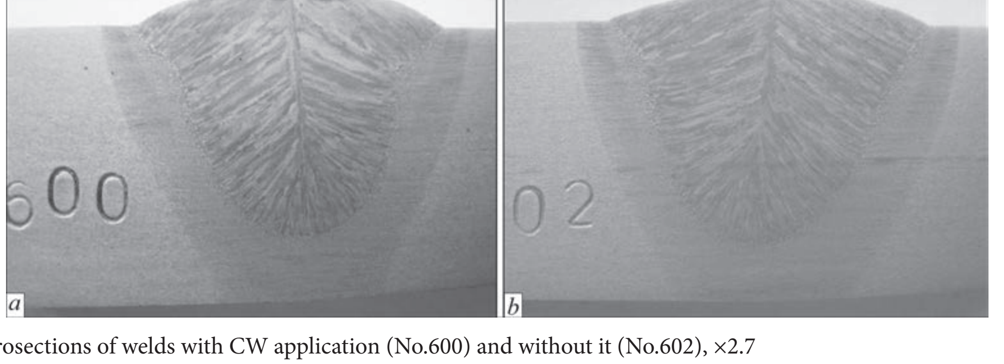

Figure 1. Macrosections of welds with CW application (No.600) and without it (No.602), ×2.7

Table 2. Process parameters and weld dimensions

Weld number	Arc number	$V_{CW f}$, mm/10 s	I_w/U_a, A/V	V_w, m/h	$V_{el f}$, mm/10 s	ψ	Weld dimensions, mm		
							h	*b*	a
603	1	205	1100/36	65	485	0.46	14.6–14.8	21.7–21.9	3.2–3.5
	2		980/38–39		443				
605	1	160	1100/36	62	497	0.34	13.5–13.7	23.0–24.4	2.9–3.2
	2		900/42–43		467				
606	1	202	1100/36	62	497	0.43	14.3–14.5	23.1–24.1	2.7–3.1
	2		900/42–43		467				

Table 3. Influence of CW and its location on weld dimensions

Weld number	Arc number	ψ	$V_{CW f}$, mm/10 s	I_w, A/U_a, V	$V_{el f}$, mm/10 s	Weld dimensions, mm		
						h	*b*	*a*
Reference weld without CW application								
702	1	0	0	1050/36	470	13.5	23.7–23.9	1.8–2.8
	2			900/42	445			
Reference welds with CW feeding behind the last arc								
700	1	0.37	165	1050/36	470	ND	23.5–24.6	3.2–4.1
	2			900/42	445			
701	1	0.48	215	1050/36	470	13.6	23.3–23.9	3.3–4.0
	2			900/42	445			
Reference weld with CW feeding between the arcs								
703	1	0.44	215	1050/36	470	13.0	24.8–25.7	3.6–4.1
	2			950/42	485			

ly 50 A. Increase of CW feed rate led to shortening of the crater length.

TEST SERIES 2 (MODE CORRECTION)

To improve weld formation the electrode feed rate in arc 2 was lowered, and the possibility of increasing CW feed rate was also tested at coefficient $\psi = 0.46$ to achieve greater cooling of the weld pool (weld No.603, Table 2). Alongside weld narrowing and anticipated increase of reinforcement height, the mentioned increase of wire feed rate also led to waviness of reinforcement edges.

Improvement of weld formation by mode No.603 was achieved by increasing the electrode spacing from 20 to 25 mm, reducing the welding speed from 65 to 62 m/h and increasing the second arc voltage (welds Nos 605, 606).

TEST SERIES 3 (INCREASE OF THE DISTANCE BETWEEN CW AND THE SECOND ELECTRODE)

Increase of the distance between CW and the second electrode was tested to stabilize the burning mode of the second arc and more effective cooling of the weld pool (Figure 2). Here, it should be limited, depending both on the welding mode and CW feed rate, to avoid lack-of-melting ("freezing") of CW in the weld pool with emergency stopping of the process. A preliminary indication of emergence of such a situation is appearance of a slag crust on the surface of longitudinal protrusions and depressions, left by CW when it sweeps up the half-molten slag crust and flux to the second arc with deterioration of its burning stability (Figure 3). In this case, the emergency situation appeared at the mentioned distance of more than 12 mm. Therefore, with the view to process stability it was reduced to 8 mm for further experiments (welds Nos 700, 701).

Experiments showed that CW "freezing" to the pool does not take place at increase of its feed rate at least to 215 mm/10 s (weld No.701), but it is accompanied by inacceptable increase of weld reinforce-

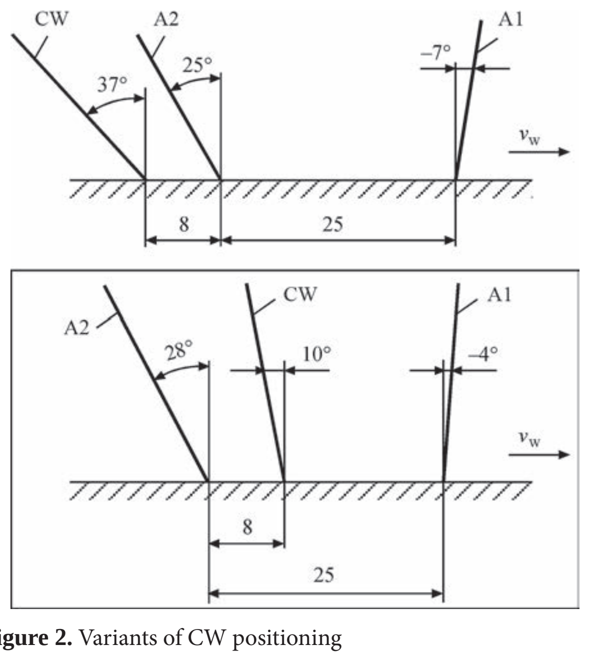

Figure 2. Variants of CW positioning

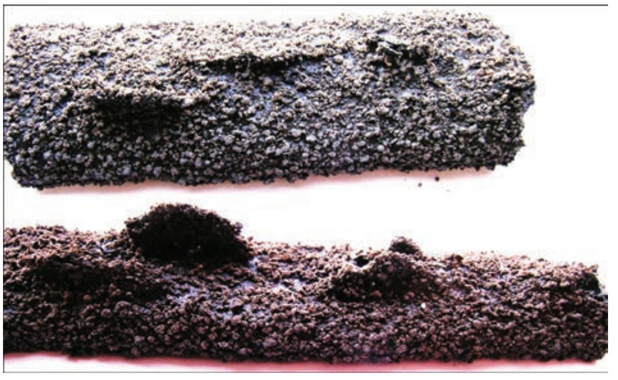

Figure 3. Unevenness of slag crust surface arising at excessive distance from CW to the last electrode

ment height (Table 3) that will require correction of the groove area.

TEST SERIES 4 (PLACING CW BETWEEN THE ELECTRODES)

Testing the variant with CW feeding between the arcs, in connection with the special features of machine design, required certain changes in the electrode setting parameters (Figure 2). Here, the quality of formation of the weld (No.703) improved as a result of positive forming effect from the action of the second arc on excess metal from CW melting (see Table 3). It is known that such CW positioning is used to increase the process productivity [5].

Chemical composition of the metal of welds on 10G2FB steel was typical for gas pipes (Table 4), ensuring their high impact toughness (Table 5). Additional alloying by Ti–B can be used to further increase the weld metal impact toughness.

Impact toughness testing of weld metal did not reveal any advantages of the process with CW application (Table 5). As to HAZ metal, similar testing showed very high spreading of the results, which did not allow an objective evaluation of the possible advantages of CW application by this characteristic.

Analysis of the microstructure of welded joints Nos 701, 703, welded with CW application, was performed in comparison with a joint made in the same mode, but without CW application (specimen No.702). Photographs of the structures of coarse-grain zone are given in Figures 4, 5.

Structure of specimen No.702 is typical for joints from steel X70. In the coarse-grain zone it is of bainitic type with different form of the second phase precipitates (Figure 4). These are ferrite grains mostly

Table 4. Chemical composition of the metal of weld, wt.% and BM

Analysis point	C	Si	Mn	S	P	Ni	Mo	V	Al	Nb	Ti
Weld	0.086	0.33	1.60	0.009	0.018	0.19	0.19	0.058	0.025	0.02	0.010
BM	0.103	0.245	1.57	0.005	0.013	0.02	<0.01	0.081	0.030	0.03	0.013

Table 5. CW influence on welded joint impact toughness

Weld number	ψ, %	*KCV*, J/cm^2			
		Weld		HAZ	
		–20 °C	–40 °C	–20 °C	–40 °C
Series 1					
602	0.00	166.2–185.2 173.6	87.5–145.6 122.9	83.1–144.3 110.1	55.8–94.7 84.7
600	0.21	159.7–172.5 166.2	97.6–144.4 123.4	62.1–245.9 126.7	38.5–90.5 60.5
Series 2					
603	0.46	169.6–256.1 199.6	106.0–157.9 129.0	63.1–219.0 133.0	42.8–142.2 78.4
605	0.34	N/D	N/D	158.2–220.7 190.1	75.3–202.2 135.6
606	0.43	N/D	N/D	68.3–245.6 158.1	107.6–153.4 127.5
Series 3, 4					
701	0.48	151.4–215.8 197.9	80.9–184.6 143.3	62.9–173.1 107.9	43.4–117.1 70.1
703	0.44	167.5–197.1 182.3	99.4–179.4 129.1	100.7–218.1 157.2	58.6–190.0 106.1
702	0.00	174.4–226.3 193.8	87.7–166.7 122.9	67.4–226.4 120.7	37.5–186.1 92.3
Note. Number of specimens tested for each variant is 5 pcs.					

with dense distribution of the ordered and unordered phases. Individual coarse ferrite grains are observed near FL, some of which have an elongated shape and are located in parallel to the above-mentioned line with sparse distribution of platelike forms of the second phase. In the zone adjacent to FL, the coarse grain corresponds to number 3–4 acc. to GOST 5639.

There can be three rows of such coarse grains near the FL. The longest extent of the coarse-grain zone is approximately 0.5 mm. A grid of continuous polygonal hypoeutectoid ferrite is present on the boundaries of primary austenite grains.

The type of microstructure in the coarse-grain zone of a welded joint of specimen No. 701, where CW was fed behind the last arc, is similar to specimen No.702. However, a greater number of grains with the prevailing fraction of the structure with an ordered form of the second phase, represented by parallel platelike packets located across the entire grain, is observed in it, while in the zone adjacent to FL, a tendency to formation of mostly grains of No.4 size, and individual grains of No.3 size is observed. The polygonal ferrite grid on the boundaries of primary austenite grains is not continuous. The extent of the coarse-grain zone does not exceed 0.42 mm.

On specimen No.703 CW application led to some more pronounced positive changes in the coarse-grain zone (Figure 5). They concern the extent (width) of the coarse-grain zone, its maximum size and structure type. So, the coarse-grain zone is reduced from 0.5 to 0.4 mm, while the maximum grain size decreases from Nos 3–4 to Nos 4–5 acc. to GOST 5639. CW also promotes improvement of the coarse grain structure, namely reduction of the volume of rack bainite in the form of extended packets, spreading through the entire grain, and increase of the volume of bainite with disoriented and globular carbide formations. Here, the greater part of the coarse grains near the FL consists of individual disoriented blocks. Reduction of the volume of hypoeutectoid ferrite fringe on the boundaries of the coarse grains in the HAZ is also observed.

MAK-phase chains were present in the overheated zone on grain boundaries in all the studied specimens.

Thus, CW application promoted a certain improvement of welded joint structure, which was manifested to the greatest extent in individual regions of the HAZ of weld No.703.

DISCUSSION OF THE RESULTS

Comparison of the modes of making welds Nos 600 and 602 (see Table 1) allowed evaluation of the energy consumed in CW melting, and determination of $t_{8/5}$ parameter. If in the initial variant No.602 the rate of wire feed on arc 2 is increased by the value of CW feed rate in variant No.600, then, proceeding from the assumption of a proportional increase of welding current, it would rise by approximately 200 A. Thus, the energy required for CW melting at coefficient ψ = = 0.21 is approximately equal to $U{\cdot}I \approx 36.200$ V·A. If self-regulation of arc 2 in process No.600 is eliminated by moving CW farther away from it, then this energy will be taken by the weld pool with its appropriate cooling and without the mentioned increase of its current. Under such conditions, reduction of heat input in the initial process No.602 at CW application, will be equal to approximately 10 %.

Parameter $t_{8/5}$ of the time of weld cooling in the temperature range of 800–500 °C is proportional to the process heat input [6]. Thus, CW application at ψ = 0.21 will reduce $t_{8/5}$ parameter also by 10 %, which is in agreement with the data of [1].

Acceleration of weld pool cooling rate using CW turned out to be insufficient for any significant improvement of the structure and noticeable increase of weld metal impact toughness. So, welds Nos 701, 703 welded using CW with rather high coefficient ψ = = 0.44–0.48 in one series with weld No.702, where

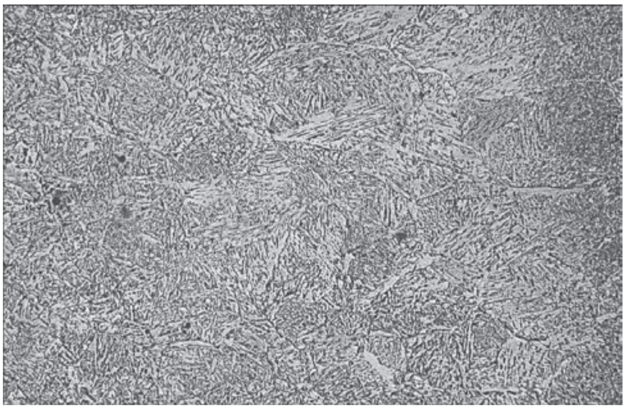

Figure 4. Microstructure (×100) of coarse-grain zone of a welded joint (No.702), made without CW application

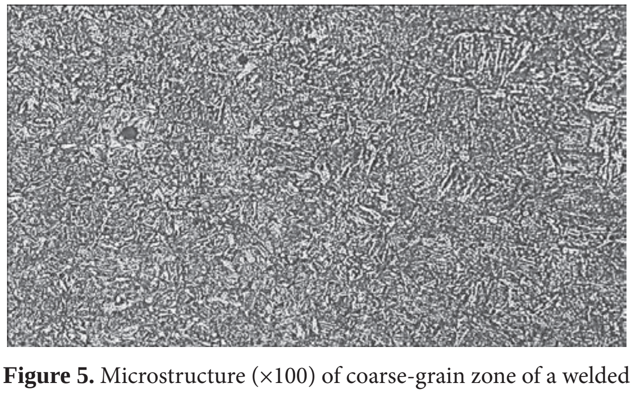

Figure 5. Microstructure (×100) of coarse-grain zone of a welded joint (No.703), made with CW application (ψ = 0.44 %)

CW was not used, demonstrated approximately the same impact toughness (see Table 5).

As regards the HAZ metal, a great spreading of impact toughness values is observed. It is largely determined by the procedure of making the notch by the standard for underwater gas pipelines [5], in keeping with which a considerable part of it runs through the coarse-grain zone.

This zone is known to be characterized by great inhomogeneity of the structure and lowering of the metal ductile properties. Here, the smallest change of FL steepness influences the portion of the notch, running through the mentioned unfavourable zone, increasing the spreading of impact toughness values.

It should be also noted that at CW positioning behind the last arc an increase of FL steepness is observed, with probable lowering of the HAZ impact toughness values.

The new process showed a certain tendency to improvement of the HAZ metal structure.

CONCLUSIONS

The possibility of implementing the process with CW application is shown under the conditions of two-wire submerged-arc welding. CW feeding is performed behind the last arc or between the arcs. The ratio of CW mass to that of the second arc electrode wire (ψ coefficient) should not exceed 0.14–0.20. Increase of this ratio will require correction of the process initial parameters.

This process does not provide any essential improvement of mechanical characteristics of the joints, but somewhat improves the HAZ metal structure and can significantly increase the deposition rate.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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