Section 2. Engineering, Environmental Science

Corrosion resistance of welded joints made by underwater wet welding

Sergey Maksimov[1], Alla Radzievskaya[2], Liudmyla Nyrkova[3], Switlana Osadchuk[4]

E.O.Paton Electric Welding Institute
K. Malevicha Str. 11, Kyiv, Ukraine, 03680
[1]maksimov@paton.kiev.ua

Отримано 29.04.2021, принято 19.05.2021
https://doi.org/10.32347/tit2141.0201

INTRODUCTION

One of the reasons of coming out of order of metal structures, operating in water environment, including sea conditions, is the corrosion. Thus, for example, the corrosion wear of metal of the ship hull underwater part can reach from 0.3 up to 0.5 mm/year. The corrosion of welds is the ever more critical situation. The rate of their fracture exceeds the rate of the base metal corrosion and in some cases it may reach 1-3 mm/year [1, 2]. The great selective corrosion in the form of fissures along the welds (on both sides) was observed in heat-affected zone (HAZ) metal of slot, butt welds and welds for welding-on to the basic workpiece, i.e. up to 1 mm/year, in some cases a through corrosion fracture of the fusion line (formation of blowholes) was observed [1]. In the opinion of the work authors [2] the welds are subjected to fracture due to the occurrence of thermal electromotive force between the parts welded under conditions of high electric conductivity of the sea water (Seebeck effect).

To repair the corroded welded joints of metal structures, operated under the water, a wet underwater welding is used. At the E.O.Paton Electric Welding Institute the specialized flux-cored wires have been developed, which are designed for welding low-carbon and low-alloyed steels, including those of a higher strength. In the latter case the electrode materials of an austenite type are used to provide resistance against cold crack formation in the HAZ [3]. The work was aimed at study of corrosion resistance of welded joints with ferrite and austenite deposited metal, made by the underwater wet welding, under the conditions, which simulate the service conditions in sea water.

MATERIALS AND METHODS OF INVESTIGATIONS

The procedure of preparation of specimens for investigations was the same as in work [4] and consisted in the following. Butt joints of steel St3 were welded in air. The groove of 8 mm depth was made along one of weld sides along the fusion line. The welding-up of grooves was made under water by flux-cored wires of ferrite and austenite type at the mode: I_w = 180...200 A, U_a = 33...34 V.

Characteristic of studied specimens of welded joints with deposited layers is given in Table 1.

Table 1

Characteristic of specimens of welded joints of pipe steel St3 with ferrite and austenite deposited metal

No. of specimen	Type of deposited metal
1	ferrite, made by flux-cored wire PPS-AN2
2	ferrite, made by flux-cored wire PPS-AN2 + 2 % Cu
3	austenite, made by flux-cored wire with Ni sheath

Corrosion tests of specimens of welded joints for a general corrosion were carried out in a running flow of 3% NaCl solution during

250 h by using the method of profilometry in accordance with OST 5.9255, item 2.3 [5],corrosion resistance under conditions of varying wetting was studied in 3% NaCl solution at temperature (20±2) °C during 250, 700, 1000 and 2000 h. Specimens were loaded by a four-point scheme up to $0.8\sigma_Y$ of base metal. After corrosion tests the region in the vicinity of deposited layer was examined by the optical microscopy method. Metallographic sections were prepared by a standard procedure.

INVESTIGATION OF RESISTANCE OF WELDED JOINT SPECIMENS OF STEEL ST3 WITH FERRITE AND AUSTENITE DEPOSITED LAYERS IN A RUNNING FLOW

The depth of corrosion fractures of specimens after tests was determined with respect to as-ground surface near edges on the specimen face side, which was isolated before tests by a protective coating.

Investigations were continued 250 h (104 days). After finishing, the specimens were taken out from the solution, corrosion products were removed and the depth of corrosion damages in width and length of a specimen was measured. Appearance of specimens before and after tests is given in Fig. 1.

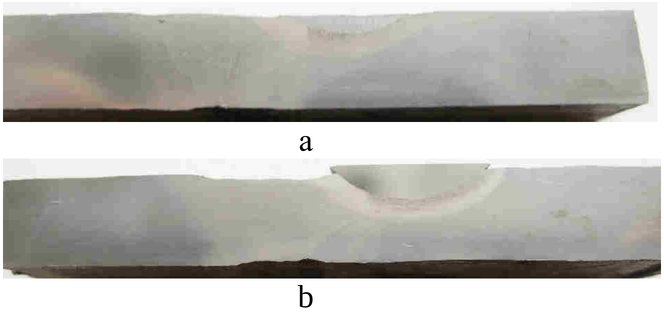


Fig. 1. Appearance of specimens with ferrite (a) and austenite (b) deposited layer after tests in a running flow during 250 h

To make quantitative assessment and analysis of corrosion features of specimens with different type of deposited metal, a mean depth of corrosion damages of different zones was determined with account for of a total number points of measurements by formulae:

$$h_{BM}^{ev} = \frac{\sum h_{BM}}{N_{BM}}, \tag{1.1}$$

$$h_{W}^{ev} = \frac{\sum h_{W}}{N_{W}}, \tag{1.2}$$

$$h_{DL}^{ev} = \frac{\sum h_{DL}}{N_{DL}}, \tag{1.3}$$

where $\sum h_{BM}$ is the sum of depth of corrosion fractures of base metal, mm; $\sum h_W$ is the sum of depth of corrosion fractures of weld metal, mm; $\sum h_{DL}$ is the sum of depth of corrosion fractures of deposited layer metal, mm; N_{BM} is the number of points of measurements of depth of corrosion fractures of base metal; N_W is the number of points of measurements of corrosion fractures of weld metal; N_{DL} is the number of points of measurements of depth pf corrosion fractures of deposited layer metal.

In accordance with OST 5.9255, item 2.3 [5], when determining the depth of corrosion fracture by the number of points of measurements, it is recommended to calculate the maximum values of depth and number of pits per one см^2 in different zones of welded joint specimens together with a mean depth. As it is seen from Fig.1, a, the corrosion in zones was spread rather uniformly and to make these calculations was not rational, therefore, the corrosion resistance of specimens was evaluated by the characteristics:

- mean depth of corrosion fractures of base metal (h_{BM}^{ev}), weld metal (h_{W}^{ev})and deposited layer metal (h_{DL}^{ev}), mm;
- rate of corrosion of base metal (P_{BM}), weld metal (P_W) and deposited layer metal (P_{DL}), мм/год;
- ratio of rate of corrosion deposited layer metal to rate of corrosion of base metal ($\frac{P_{DL}}{P_{BM}}$);
- ratio of rate of corrosion of weld metal to rate of corrosion of base metal ($\frac{P_W}{P_{BM}}$).

Rate pf corrosion of base metal, weld metal and deposited layer metal was calculated by formulae:

$$P_{BM} = h_{BM}^{ev}\frac{365}{\tau}, \tag{1.4}$$

$$P_{W} = h_{W}^{ev}\frac{365}{\tau}, \tag{1.5}$$

$$P_{DL} = h_{DL}^{ev}\frac{365}{\tau}, \tag{1.6}$$

where τ is the duration of tests in running solution, days; 365 is the number of days in year.

From the results of measurements of depth of corrosion fractures the profilograms were plotted, which are given in Fig. 2, for more visual representation of corrosion nature along the zones of welded joint with a repair weld.

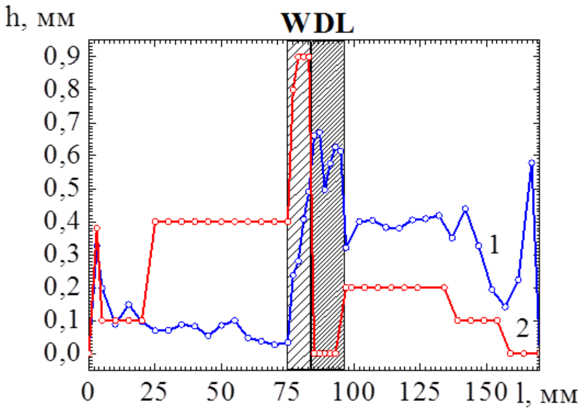


Fig. 2. Profilogram of surface after specimens testing in running flow during 250 h
1 – ferrite DL, made by wire PPS AN-2 + 2 % Cu;
2 – austenite DL, made by wire of Ni strip

Results of assessment of corrosion resistance of test specimens are given in Table 2. It follows from the analysis of obtained results that for a specimen with ferrite repair weld the rate of corrosion in the region of W and DL was almost twice higher than that of BM (Table 2, line 1). On the specimen with austenite DL the rate of corrosion of DL is equal to zero, and the highest corrosion fracture was shown in W, as the corrosion rate in this zone is more than three times higher than that of BM (Table 2, line 2). Table 3 presents for reference the ten-point scale of corrosion resistance of metals, according to which the corrosion resistance of specimen different zones was evaluated.

Results of corrosion investigations have a good correlation with data of potentiometry: the larger difference of potentials between BM and DL and W and DL, the higher is the rate of corrosion of WJ zone.

The conclusion can be made on the basis of the obtained results that in the running flow of sea water the different zones of welded joint with studied ferrite and austenite DL have the following corrosion resistance:

- BM - group IV, “comparatively resistant” (point 7 by GOST 13819, Table 3)
- W - group V, “low-resistant” (point 8 by GOST 13819, Table 3)
- ferrite DL, made by wire PPS AN-2 + 2% Cu - group V, “low-resistant” (point 8 by GOST 13819, Table 3)
- austenite DL, made by wire of Ni strip - group I, “absolutely resistant” (point 1 by GOST 13819, Table 3).

On the basis of analysis of the obtained experimental results it can be stated that W and ferrite DL, deposited by wire PPS AN-2 + 2% Cu will be mainly subjected to fracture in the running flow of sea water

Table 2
Results of assessment of corrosion resistance of welded joint different zones

Characteristic of specimens	Mean depth of corrosion damages of different zones, mm			Corrosion rate in different zones, mm/year			Ratio of corrosion rate in W/DL metal to corrosion rate in	
	h_{BM}^{ev}	h_W	h_{DL}^{ev}	P_{BM}	P_W	P_{DL}	$\frac{P_W}{P_{BM}}$	$\frac{P_{DL}}{P_{BM}}$
with ferrite DL (PPS AN-2 + 2 % Cu)	0.21	0.42	0.53	0.75	1.46	1.86	1.94	2.48
with austenite DL (Ni strip)	0.26	0.88	0	0.90	3.07	0	3.41	0

As the corrosion resistance of different zones of WJ with DL was greatly differed, and in the conditions of WJ loading their further local fracture can occur, the stability of WJ under conditions of effect of tensile stresses was investigated.

After investigations in the running flow the WJ specimens were subjected to bending with a deposited layer outside up to the formation of the first crack or at 180° angle in cases when the crack was not formed, and then the metallographic examinations were carried out.

Table 3

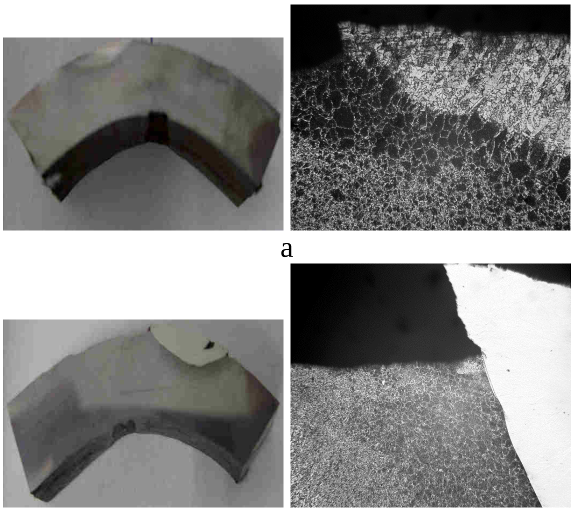
Ten-point scale of corrosion resistance of metals

Group of resistance	Rate of metal corrosion, mm/year	Scale point
1 Absolutely resistant	less than 0,001	1
2 Rather resistant	from 0.001 up to 0.005	2
	from 0.005 up to 0.01	3
3 Resistant	from 0.01 up to 0.05	4
	from 0.05 up to 0.1	5
4 Less resistant	from 0.1 up to 0.5	6
	from 0.5 up to 1.0	7
5 Low-resistant	from 1.0 up to 5.0	8
	from 5.0 up to 10.0	9
6 Not-resistant	more then 10.0	10

The metallographic sections were prepared by the standard procedure, applying diamond pastes of different dispersity. To reveal the microstructure the specimens were etched in NITAL (solution of 4% nitric acid in ethyl alcohol). Metallographic examinations were carried out in microscope NEOPHOT 21 at magnifications ×80, ×100, ×125, ×200. Digital image of microstructure of specimens was obtained by means of photo camera Olympus C 5050.

Figure 3 presents appearance of a fragment of a central part of WJ specimens of steel St3 with a ferrite deposited layer, made by wire PPS AN-2 (Fig. 3, a) and austenite DL, made by wire of Ni strip (Fig. 3, b), and microstructure of near-surface layers of DL.

As is seen from the analysis of experimental data, after investigations in the conditions of varying wetting, the cracks were not observed along the fusion line of DL/W in none of specimens of WJ with DL, which proves their resistance under the conditions of effect of tensile stresses.


a

b

Fig. 3. Appearance of a fragment of a central part of WJ specimens of steel St3 with a ferrite DL and microstructure of near-surface layers, made by wire PPS AN-2 (a) and austenite DL, made by wire of Ni strip (b), after study of resistance against corrosion cracking in a running flow during 250 h and bending up to initiation of the first crack, ×80

INVESTIGATION OF RESISTANCE OF WELDED JOINT SPECIMENS OF STEEL ST3 WITH FERRITE AND AUSTENITE DEPOSITED LAYERS IN THE CONDITIONS OF VARYING WETTING

Tests of resistance of specimens of base metal and welded joints under the conditions of the varying wetting were performed in 3% NaCl solution at temperature T = 295 K and level of load 0.8 σ_y of base metal during 250, 700, 1000 and 2000 h.

After 250 h of tests in a running flow the metallographic examinations were carried out. An analysis of experimental data has shown that destruction occurs the BM fracture was occurring uniformly in all the WJ, mainly in W. On DL, made by wires PPS AN-2 and PPS AN-2 + 1% Cu, the deep corrosion pits are seen. Corrosion of DL, made by wire PPS AN-2 + 2% Cu, is more uniform than in two previous cases. DL, made by wire of NI strip, remained without changes. Local corrosion damages in the form of cracks were not observed in none of WJ.

Due to different corrosion resistance of zones of WJ with DL their cracking could be occurred in the conditions of WJ loading, therefore after the action of the varying wetting during different period of time the effect of compressive and tensile stresses were studied. For this purpose, after tests for varying wetting the specimens were subjected to bending up to initiation of the first crack or at 180° angle, if the cracks were not observed, and then the metallographic examinations were carried out,

For specimens with DL after holding at varying wetting during 700 h the resistance to the effect of compressive stresses was investigated, and for the longer time, i.e. 1000 and 2000 h, the effect of tensile stresses was investigated.

It should be noted that after bending the specimens, which were tested during 700, 1000 and 2000 h the depth of corrosion pits was visually smaller, than on flat specimens, that can be predetermined by the tension of surface layer of metal, which was subjected to the effect of tensile stresses. The same as in the previous case, the more intensive fracture occurred in W than in DL (Fig. 4). This was more pronounced on WJ and DL, made by wire from Ni strip, on the photo of which it is seen that the austenite layer remained without changes (Fig. 4, c) during corrosion tests in the conditions of varying wetting. The local corrosion damages in the form of cracks were not revealed in none of WJ.

CONCLUSIONS

In a moving stream of seawater after 250 hours, various WJ zones with the studied ferritic and austenitic DL have the following corrosion resistance:

- base metal - group IV, “relatively stable”, ball 7 according to GOST 13819;
- weld - group V, “low stability”, ball 8 according to GOST 13819;
- ferritic DL made with PPS AN-2 + 2% Cu wire - group V, “low stability”, ball 8 according to GOST 13819;
- austenitic DL, made with Ni tape - group I, “absolutely stable”, score 1 according to GOST 13819.

On the basis of the obtained results, it was established that in a moving stream of seawater, a weld and a ferritic DL made of PPS AN-2 + 2% Cu will be predominantly destroyed by ulceration.

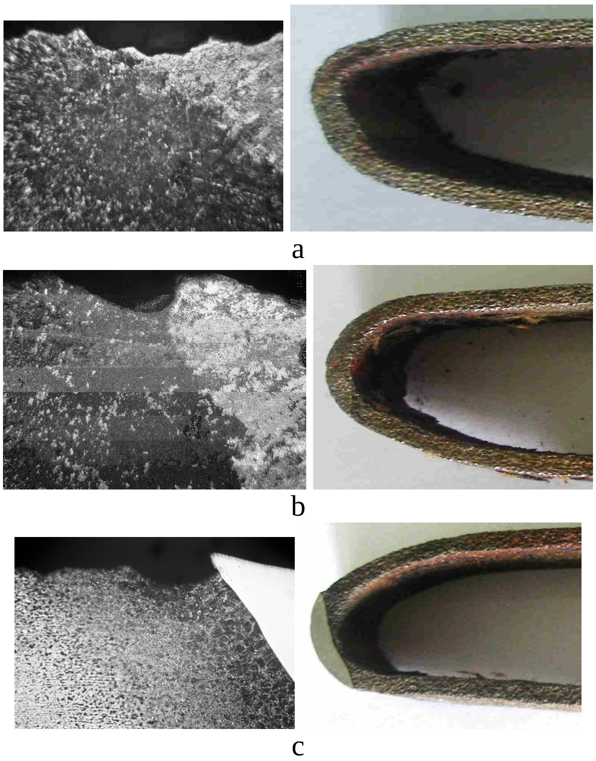


Fig. 4. Appearance of WJ specimen of steel St3 with DL and microstructure of near-surface layers, made by wire PPS AN-2 (a), PPS AN-2 + 2% Cu (b) and wire of Ni strip (c) after investigation of resistance against corrosion cracking in the conditions of varying wetting during 2000 h and bending, × 100

Under conditions of alternating wetting with a solution of 3% NaCl for 2000 hours, the destruction of welded joints of St3 steel with ferritic and austenitic weld layers developed more intensively along the welds compared with the weld layers and the base metal. Metallographic studies confirmed the absence of local corrosion damage in the form of cracks along the fusion line of the weld with the weld layer on all the welded joints studied.

Keywords: underwater welding, welded joints, sea water, corrosion.

REFERECES

1. Kolomijtsev E.V. (2012) Corrosion resistance of welded joints of ship hull materials. Avtomatich. Svarka, 4, 59-64.

2. Sirotyuk A.M., Dmitrakh I.M. (2014) Assessment of corrosion-mechanical defects of underwater pipeline steels. Visnyk of admiral Makarov NUK, 2, 66-72.
3. Maksimov S.Yu., Savich I.M., Zakharov S.M. (2003) Structure and properties of metal, deposited under water by flux-cored wire with Ni sheath. Avtomatich. Svarka, 4, 19-22.
4. Gusachenko A.I., Savich I.M., Los E.P. (1987) Corrosion of welds of welded joints of hull steels of 09G2 type and possibility of their underwater sealing welding. Avtomatich, Svarka, 11, 58-60.
5. OST 5.9255–76. Metals and coatings for ship building. Methods of express corrosion tests.
6. GOST 9.901.2-89. Standard system of protection from corrosion cracking of specimens in the form of bent bar.