CORROSION RESISTANCE OF WELDED JOINTS OF SHIP HULL MATERIALS

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Experience of operation of sea ferries is indicative of nonuniform general corrosion of hulls in the area of welded joints. The objective of this work was investigation of corrosion resistance of ship hull steels and their welded joints for the conditions of operation of «Sakhalin» series ferries of the second generation. Investigation procedure envisaged assessment of corrosion characteristics of ship hull materials under diverse conditions: determination of stationary electrode potentials and rate of general corrosion of low-alloyed hull steels, investigation of corrosion resistance of welded joints of these steels in rapid sea water. Obtained results allow recommending the following steels as base metal for hulls of «Sakhalin» series ferries of the second generation: for ice belt — steels of 15GB and 10GNB grades, for outer shell of hull underwater part, inner bottom and partitions — steels of A27 and D32 grades to TU-14-1-4264–87. Welding of steels 15GB, 10GNB and A27 should be performed both by nickel-containing and nickel-free consumables. Steel D32 can be welded by nickel-free consumables. 10 Ref., 6 Tables, 1 Figure.

Keywords: *corrosion resistance, hull steels, welded joints, electrode potentials, sea water, testing duration*

Over the recent decades ship service conditions became much more stringent. Ship movement speed increased, and geography and intensity of their navigation became greater. Such ships, in particular include «Sakhalin» series ferries, operated in Tatar Straight. Hulls of ferries, made from manganese steels 09G2 and 10G2S1D (ice belt), are prone to non-uniform corrosion, particularly in the near-weld zone. This leads to the need to weld up the damaged locations and replacement of the shell plates that increases the duration and cost of dock repairs, while lowering the operating effectiveness.

As ship hulls have been made welded and not riveted for more than 70 years, and corrosion resistance of welded joints quite often is greatly inferior to corrosion resistance of base metal, this necessitates performance of corrosion testing of welded joints.

There is quite extensive material on corrosion resistance of carbon and low-alloyed weldable hull steels in sea water [1–5].

Corrosion of 09G2 steel is characterized by considerable non-uniformity of surface damage. Average corrosion rate is 0.16–0.25 mm per year. With increase of sea water current speed up to 10 m/s in regions with moderate climate the rate of corrosion of low-alloyed steels can rise up to 1 mm per year [3, 4].

Corrosion wear of plates of outer shell of «Sakhalin» ferry hulls was equal to 0.3–0.5 mm per year. The greatest relative thinning was observed in the plates of bottom and bilge shell. Considerable corrosion damage was found in areas of site welds, made by manual welding, as well as in points of weld crossing and in the area of settling tank.

Enhanced selective corrosion in the form of furrows along the welds (from both sides) was observed in the metal of HAZ of slot and butt welds and welds of joining the main framework — up to 1 mm per year, and in a number of cases through-thickness rusting (blowholes) were found, which are readily visible in the Figure. Furrow fractures of HAZ metal are a consequence of enhanced corrosion of anode (hardened) zone adjacent to the weld [4].

In view of enhanced corrosion wear of outer shell of «Sakhalin» ferries after 8–10 years of operation, it was necessary to replace panels of the total area of up to 1800 m^2 and make up to 2000 m of welds.

Causes for increased corrosion wear of underwater part of «Sakhalin» ferries are as follows:

- ineffectiveness of recommended measures of anticorrosion protection at operation in the ice conditions;
- insufficient corrosion-erosion resistance of 10G2S1D, 10KhSND and, particularly, 09G2 steels.

One of the ways to solve this problem is application of new hull materials with increased corrosion resistance, as well as strict following of welding technology, including selection of welding consumables.

The objective of this work was investigation of corrosion resistance of new and currently available hull steels and their welded joints, as well as selection of optimum combinations of base materials and welding consumables to increase the resistance (fatigue life) of hulls of «Sakhalin» ferries of the second generation. Selection of low-alloyed hull steels was based on their corrosion resistance exceeding that of steel of 09G2 grade, while the welded joint resistance should be on the level of that of base metal, i.e. an optimum combination of steel grades, welding consumables and their welding technology is required.

To study the corrosion resistance of base metal and welded joints, standard samples of (10–14) × × 80 × 200 mm size to OST 5.9255–76 [6] were cut out of steel of 09G2, A27, D32, 15GB, 10KhSND and 10GNB grades.

Steels of 09G2, A27 and 15GB grades have been normalized, D32 (TU 14-1-4264–87) [7], 10KhSND and 10GNB (TU 14-1-4603–89) [8] have been subjected to quenching with tempering.

Composition and mechanical properties of the studied steels are given in Tables 1 and 2, respectively.

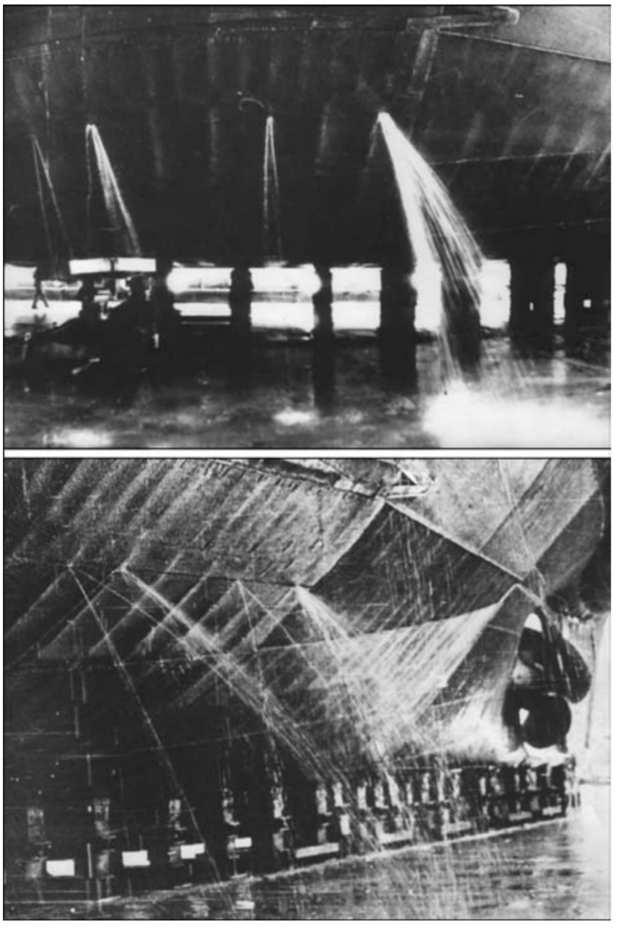
Welded joints were made by manual, semiautomatic and automatic welding with application of nickel-free and nickel-containing welding consumables. Table 3 gives welding consumables and welding modes.

Each variant of steel grade, welding process, and welding consumable is represented by three samples. Investigations included:

• determination of stationary electrode potential of the base metal and corrosion rate values by mass method in quiet sea water;

• determination of corrosion values of welded joints in rapidly moving artificial sea water (ASW) with strip chart recording.

Determination of stationary electrode potential was conducted in quiet ASW of oceanic composition [9] on samples of 5 × 30 × 50 mm size. Measurements were conducted with application of digital voltmeter Shch-1413, saturated calomel electrode was used as reference electrode, and then measurement results were recalculated for hydrogen electrode.



Corrosion damage (blowholes) in outer plating of underwater part of «Sakhalin» ferries of the first generation

Determination of corrosion rate in quiet ASW (testing base of 3000 h) was conducted by mass method. Then, considering the relatively uniform nature of corrosion of these steels the value was recalculated into depth index and averaged by three samples.

Results of measurement of potentials and corrosion rate of low-alloyed steels are given in Table 4.

As is seen from the Table values of electrode potentials of 10KhSND, 10GNB, 15GB, A27 and D32 steels are close and are equal from −0.45 up to −0.48 V, and for 09G2 steel they are more

Table 1. Composition of hull steels, wt.%

Steel grade (category), GOST, TU	C	Mn	Si	S	P	Ni	Cr	Cu	Al	Ti	Nb
09G2, GOST 5521–93	0.10	1.65	0.32	0.022	0.032	0.03	0.02	0.05	0.014	–	–
D32, GOST TU 14-1-4264–87	0.09	1.24	0.28	0.035	0.023	0.20	0.11	0.30	0.050	0.017	–
15GB (E36), GOST 5521–93	0.16	1.30	0.31	0.012	0.017	0.08	0.06	Traces	0.021	0.009	0.020
10KhSND (E40), GOST 5521–86	0.10	0.53	0.84	0.023	0.015	0.65	0.70	0.50	0.021	–	–
10GNB (E40), TU 14-1-4603–89	0.10	1.37	0.33	0.005	0.020	0.77	0.05	0.12	–	–	0.034
A27, TU 14-1-4264–87	0.11	0.47	0.22	0.029	0.012	0.23	0.10	0.38	–	–	–

Table 2. Mechanical properties of the studied steels

Steel grade (category), GOST, TU	Plate thickness, mm	Tensile strength σ_t, MPa	Yield limit σ_y, MPa	Relative elongation, δ, %	Impact energy KV, J, at T, °C		
					0	−40	−60
09G2, GOST 5521–86	15	523	363	34.0	–	62; 38; 50	–
D32 (E32), TU 14-14264–87	20	510	345	27.0	–	180; 190; 180	–
15GB, GOST 5521–86	16	517	365	33.6	–	62; 38; 50	–
10KhSND, GOST 5521–86	32	540	405	31.6	–	74; 69; 64	–
10GNB, TU 14-1-4603–89	10	570	468	29.3	–	–	215; 251
A27, TU 14-1-4264–87	18	435	295	35.0	124; 103	–	–

Table 3. Welding consumables and welding modes

Welding process	Welding consumables	Electrode diameter, mm	Welding modes		
			I_w, A	U_a, V	v_w, m/h
Manual	Electrodes ITS-4 S, UONI-13/45	4.0	140–160	–	–
	E-138/50N	5.0	180–200	–	–
CO_2 semi-automatic	Welding wire of Sv-08G2S, Sv-08GSNT	1.2	140–160	22–24	–
	Sv-08GSMT	1.6	180–200	22–24	–
Automatic submerged-arc	Welding wire Sv-08A, Sv-10GN, flux OSTs-45	5.0	850–900	40–42	28–30

negative from −0.48 up to −0.50 V. Corrosion rates are distributed approximately the same way, namely in 15GB, 10KhSND and 10GNB steels depth index is 0.069–0.071 mm per year; in 09G2 steel it is 0.074. Testing in quiet water of steels of category A27 and D32 was not conducted.

Thus, proceeding from obtained results, it can be noted that steels A27, D32, 15GB, 10KhSND and 10GNB have higher corrosion resistance compared to steel 09G2. For A27, D32, 10KhSND and 10GNB steels this is attributable to higher content of nickel and copper in them. For 15GB steel this point remained unclear.

Corrosion testing of welded samples was conducted in rapidly moving medium in keeping with the requirements of OST 5.9255–76.

Testing parameters were as follows: medium of ASW, medium temperature of 32±2 °C, rate of 10 m/s, and testing duration of 1000 h.

Table 4. Stationary electrode potentials and corrosion rates of the studied steels in quiet medium (ASW)

Steel grade	Stationary electrode potential, V	Depth index of corrosion rate, mm/year
09G2	−0.48 – −0.50	0.074
A27	−0.45 – −0.46	–
D32	−0.45 – −0.46	–
15GB	−0.46 – −0.47	0.070
10GNB	−0.47 – −0.48	0.071
10KhSND	−0.45 – −0.47	0.069

After testing strip chart recording of the surface of samples subjected to corrosion was performed by the method of continuous scanning with application of electron-mechanical surface contour recorder EMP-1. Profile charts of sample surface were recorded in four tracks in 1:1 scale along abscissa axis, and 200:1 along ordinate axis.

Testing results are averaged over three samples and are given in Table 5.

As is seen from Table 5, values of average corrosion rates of base metal of A27, D32, 09G2 and 15GB steels do not essentially differ from each other, and are equal to 0.94–1 mm per year at maximum rate of 1.49–2.03 mm per year.

Average corrosion rate of base metal of 10KhSND and 10GNB steels is equal to 0.62–0.70 mm per year that is essentially higher than

Table 5. Maximum and average corrosion rates of base metal of welded joints of the studied steels

Steel grade	Corrosion rate, mm/year		Index of corrosion non-uniformity
	Max	Average	
09G2	1.46	0.97	1.51
D32	1.95	0.94	2.07
15GB	1.46	0.98	1.49
10GNB	1.06	0.62	1.71
10KhSND	1.26	0.70	1.80
A27	2.03	1	2.03

Table 6. Corrosion resistance indices of metal of welded joint zones of the studied steels in rapidly-moving medium

Steel grade	Welding process	Welding consumable grade	Indices of corrosion rate of welded joint zone, mm/year						Indices of nonuniformity of corrosion		
			Base metal		HAZ		Weld metal		max BM / av BM	av HAZ / av3 BM	av weld / av BM
			Max	Average	Max	Average	Max	Average			
09G2	Manual	ITS-4S	1.24	0.83	1.49	1.18	0.74	0.53	1.49	1.42	0.64
		E-138/50N	1.31	0.86	1.46	1.16	0.71	0.41	1.52	1.35	0.48
	Semi-automatic	Sv-08G2S	1.70	1.18	1.66	1.28	1.74	1.32	1.44	1.08	1.12
		Sv-08GSNT	1.28	0.94	1.82	1.55	0.38	0.25	1.36	1.65	0.27
	Automatic	Sv-08A	1.50	1.01	1.55	1.14	1.66	1.21	1.49	1.13	1.20
		Sv-10GN	1.71	0.98	1.48	1.13	1.67	0.88	1.74	1.15	0.90
D32	Semi-automatic	Sv-08G2S	2.07	0.98	1.24	0.74	1.98	1.15	2.11	0.76	1.17
		Sv-08GSNT	1.86	0.99	1.29	0.83	0.90	0.51	1.88	0.84	0.52
	Automatic	Sv-08A	1.78	0.86	1.25	0.81	1.62	0.81	2.07	0.94	0.94
		Sv-10GN	2.07	0.94	0.84	0.60	0.92	0.48	2.20	0.64	0.51
A27	Manual	ITS-4S	2.22	1.20	1.36	0.93	2.51	1.14	1.85	0.78	0.95
		E-138/50N	1.97	1.03	1.07	0.79	0.98	0.57	1.91	0.77	0.55
	Semi-automatic	Sv-08G2S	1.93	1.01	1.18	0.73	2.70	1.78	1.91	0.72	1.76
		Sv-08GSNT	2.10	0.96	1.09	0.70	1.32	0.73	2.18	0.73	0.77
	Automatic	Sv-08A	1.75	0.83	1.24	0.79	1.78	0.83	2.11	0.95	1
		Sv-10GN	3.19	0.99	1.15	0.74	1.39	0.11	2.21	0.75	0.72
10GNB	Manual	UONI-13/45	1.03	0.55	0.77	0.57	1.30	0.77	1.81	1.04	1.40
15GB (E36)	Manual	ITS-4S	1.24	0.81	1.04	0.83	1.14	0.78	1.53	1.02	0.96
		E-138/50N	1.25	0.88	0.98	0.72	0.79	0.53	1.42	0.82	0.60
	Semi-automatic	Sv-08G2S	1.18	0.82	0.90	0.72	1.61	1.25	1.44	0.88	1.52
		Sv-08GSNT	1.75	1.30	1.49	1.25	0.98	0.77	1.35	0.96	0.59
	Automatic	Sv-08A	1.58	1.14	1.42	1.02	1.81	1.25	1.39	0.89	1.10
		Sv-10GN	1.73	0.94	1.41	1.10	1.35	0.98	1.84	1.17	1.04
10GNB (E40)	Manual	E-138/50N	1.19	0.74	0.95	0.67	1.17	0.74	1.61	0.91	1
	Semi-automatic	Sv-08GSMT	1.00	0.56	0.77	0.54	1.15	0.86	1.79	0.96	1.54
	Automatic	ITS-4S	1.08	0.59	0.78	0.54	1.20	0.66	1.83	0.92	1.12
		E-138/50N	0.95	0.57	0.55	0.42	0.84	0.53	1.67	0.74	0.93
10KhSND (E40)	Manual	ITS-4S	1.24	0.65	0.69	0.39	1.02	0.63	1.91	0.60	0.97
		E-138/50N	1.26	0.72	0.73	0.43	0.89	0.53	1.75	0.60	0.74
	Semi-automatic	Sv-08G2S	1.25	0.72	0.97	0.51	1.32	0.96	1.74	0.71	1.33
		Sv-08GSNT	1.29	0.70	0.70	0.51	0.77	0.58	1.84	0.73	0.83
	Automatic	Sv-08A	1.41	0.76	0.58	0.43	1.27	0.94	1.86	0.57	1.24
		Sv-10GN	1.16	0.65	0.58	0.43	0.64	0.51	1.78	0.66	0.78

corrosion resistance of 09G2, A27, D32 and 15GB steels.

Values of corrosion resistance of various zones of welded joints of the studied steels in rapidly moving medium are given in Table 6.

Corrosion resistance of welded joint zones was evaluated relative to corrosion resistance of base metal, considering it to be satisfactory, when the rate of weld or HAZ metal corrosion was in the ranges of 0.8–1.2 of that of base metal [10].

Proceeding from analysis of data in Table 6 the following should be noted:

- corrosion resistance of welds made by nickel-free welding consumables (ITS-4S, UONI-13/15, Sv-08G2S, Sv-08A) for all the steels is, usually, equal to or lower than that of base metal;
- corrosion resistance of welds made by nickel-containing welding consumables (E-138/50N, Sv-08GSNT, Sv-10GN) is higher or equal to that of the base metal.

Considering the corrosion resistance of HAZ metal, it can be noted that more intensive corrosion of HAZ metal is observed in 09G2 steel for all the welding processes. In other cases, corrosion resistance of HAZ metal is equal to or higher than that of the base metal. So, for welded joints of steels of 15GB and 10GNB grades equivalent resistance of HAZ metal compared to base metal is observed, and for 10KhSND, A27 and D32 steels increased corrosion resistance of HAZ metal is found.

Thus, HAZ metal has optimum corrosion resistance in welding D32 steel by nickel-free consumables; for steels 15GB and 10GNB — in welding both by nickel-containing, and nickel-free consumables; for A27 steel — in manual welding by both kinds of consumables, and in automatic welding by nickel-free wire.

Analysis of the data on corrosion resistance of weld metal reveals that the highest uniformity of corrosion of weld and base metal in noted in the cases of combination of base metal and welding consumable with close chemical composition. At application of nickel-containing welding consumables the most favourable results were obtained for steels of 10KhSND and 10GNB grades. For steel of 09G2, A27, D32 grades the best results were obtained at application of nickel-free welding consumables.

Integral estimation of corrosion resistance of both the HAZ and weld metal leads to the conclusion that only A27, D32, 15GB and 10GNB steels meet the requirements of equivalent resistance of welded joint zones.

Considering the requirements of designers that steels of strength grade 36 or 40 are required for the ice belt, and those of grades 27 or 32 — for the outer plating of underwater part, the following materials were recommended for «Sakhalin» ferries of the second generation:

- for the ice belt: steels of 15GB (E36, GOST 5521–86) and 10GNB grades (E-40, TU 14-1-4603–89). Automatic welding can be performed both by nickel-containing and nickel-free consumables, and manual welding — by nickel-free consumables for 15GB steel and nickel-containing consumables for 10GNB steel;
- for the outer plating of underwater part, inner bottom and partitions: A27 and D32 steels, welded joints on which should be made by nickel-free consumables. Erection joint of the ice belt with the ship lower part should be made by nickel-free consumables in welding 15GB to A27 and D32 steels, or nickel-containing consumables in welding 10GNB to A27 and D32 steels.

Furtheron it is rational to conduct investigations of corrosion resistance of welded joints of steels in such a combination as D32 steel to steels of grades 15GB and 10GNB.

Conclusions

1. 09G2 and 10G2S1D steels (GOST 5521–86) in the outer plating of the hull of «Sakhalin» ferries of the first generation have insufficient corrosion resistance, that leads to the need of replacement every 8 to 10 years of up to 2000 m^2 of plating in each ferry.

2. From the studied steel grades the corrosion resistance exceeding that of 09G2 steel is found in A27, D32 (TU 14-1-4264–87), 15GB (E36), 10KhSND and 10GNB steels.

3. From the viewpoint of corrosion resistance of welded joints for operation in the hull of «Sakhalin» ferries, the following materials can be recommended:

- for the ice belt: steels of 15GB (E36, GOST 5521–86) and 10GNB grades (E-40, TU 14-1-4603–89);
- for the outer plating of underwater part, inner bottom and partitions: A27 and D32 steels to TU 14-1-4264–87.

4. Welding of steels 15GB, 10GNB and A27 by manual and automatic processes can be performed by nickel-containing and nickel-free consumables. D32 steels should be welded by nickel-free consumables.

5. The above recommendations on application of rolled stock from the concrete steel grades (A27, D32 and E36) to GOST 5521–86 and TU 14-1-4264–87 also concern all the grades within the respective strength grade (27, 32 and 36).

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