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Determination of the corrosion resistance of the welded steels used in underwater marine systems (including the submerged parts of Wave Energy Converters)

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Abstract

The experimental investigation of the corrosion resistance of welded shipbuilding and submarine steels with the optimum weld quality which can be used in the future for the improvement of the quality of already existing underwater marine systems (including oil platforms, bridge columns and ships) and for the construction of new and unfamiliar underwater sea-structures (including the submerged parts of Wave Energy Converters and Tidal Energy Converters) in many countries like Greece is an essential parameter from a technical, qualitative and economical point of view. This study presents, justifies and discusses the outputs of the experimental investigation of the corrosion resistance of three different welded steels (HY 100 steels, 316Ti and S355J2+N) which are currently used in shipbuilding and submarine constructions.

Keywords: corrosion rate; salt spray test; HY 100 steel; S355J2+N steel; 316Ti steel; FCAW process

1. Introduction

The low corrosion resistance is one of the most important problems which causes qualitative deteriorations and rapid failures of the marine constructions and decreases the human safety and reliability [1]. All welded marine constructions are constantly affected by the corrosive seawater and by the environments with increased humidity [1]. On April 1963 the nuclear submarine USS Thresker was sunk, all 129 crew and shipyard personnel abroad were killed, and the radioactive power unit was detected in the floor of the Atlantic Ocean due to the failure of a defective soldered joint in a seawater system [1].

This article presents, analyses and compares the results obtained from the experimental determination of the corrosion rate/corrosion resistance of the three following different welded steels with the optimum weld quality which are currently used in shipbuilding and submarine constructions:

- HY 100 is an 100000 – psi high yield strength quenched and tempered fully killed and non – magnetizable steel with a good combination of strength and toughness which is used for submarine constructions and has many industrial applications in pressure vessels [2,3]. The basic advantages of the HY steel materials are their excellent

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resistance to underwater explosion shocks and their good weldability in heave thicknesses with little preheat or no post weld heat treatment [2,3].

- The X6CrNiMo17-12-2 (316Ti) austenitic stainless steels are steels with titanium stabilization, the nominal chromium content higher than 16 percent and an excellent notch toughness at cryogenic temperatures [4]. The principal advantages of 316Ti steels are their higher corrosion and oxidation resistance than the standard grades of 316, their better ductility and toughness than carbon and alloy steels and their good maintenance at elevated temperatures for a longer period without the presence of precipitation taking place [4,5].
- S355J2+N steel is a hot rolled normalized structural steel with a minimum yield strength of 355 N/mm^2 which has many common applications due to its excellent mechanical properties [6].

The chemical composition of the three previously mentioned steels, which has been determined with the aid of Optical Emission Spectrometry in accordance with the specification ASTM E415 [7], is presented in table 1.

Table 1. Chemical composition of HY 100 steel, S352J2+N steel and 316Ti steel (wt %)

Element	HY 100 steel (wt %)	S355J2+N steel (wt %)	316Ti steel (wt %)
C	0.14	0.12	0.04
Si	0.23	0.34	0.42
Mn	0.31	1.4	1.5
P	0.01	2.01	0.03
S	< 0.01	< 0.01	< 0.01
Cr	1.5	0.04	16.9
Ni	2.9	0.14	10.8
Mo	0.44	0.01	2.0
Al	0.04	0.03	---
Cu	0.01	0.18	0.31
Co	---	---	0.12
Ti	---	---	0.38
V	---	---	0.10
W	---	---	0.10

The optimum arithmetic values of the welding parameters (welding current, welding voltage and welding speed) and consequently the optimum weld quality of the three previously mentioned steels have already been experimentally determined with the aid of robotic Flux Cored Arc Welding (FCAW) Process [8]. Welding experimental execution between dissimilar steels or with a dissimilar filler metal was not investigated due to the possible susceptibility of these welds in the electrochemical corrosion [9].

2. Experimental methodology

The experimental investigation of the corrosion resistance of three different welded steel specimens was executed with the aid of Salt Spray Test. Salt Spray Test is a well – known accelerated test method which is used for the evaluation of the corrosion resistance of various materials (e.g. painted or coated materials, electrical connectors) subjected to controlled corrosive environments [10, 11]. Generally, the most common specifications for the execution of the Salt Spray Test are ASTM B117 [10], MIL – STD – 810 [13] and ISO 9227 [14]. The apparatus (see Fig.1) required for salt spray (fog) exposure consists of a fog chamber/cabinet, one reservoir with salt solution, a compressed air supply, one or more atomizing nozzles, suitable supports for positioning the welded specimens, chamber heater and necessary means of control [10].

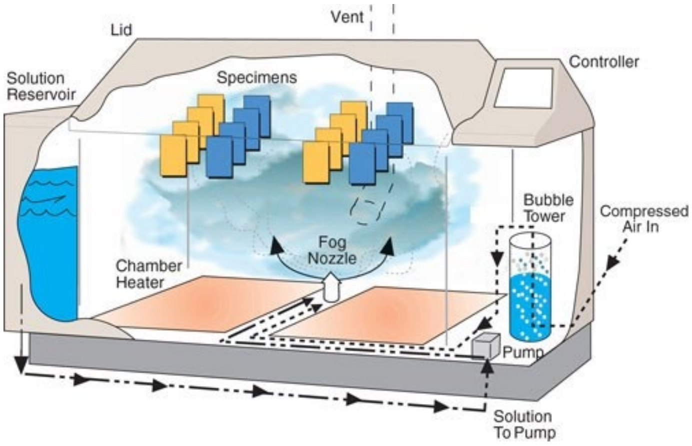

Fig. 1. Schematic view of Salt Spray (Fog) Apparatus [15]

The HY 100 welded steel specimen, the 316Ti austenitic stainless welded steel specimen and the S355J2+N welded steel specimen with the optimum weld quality were selected for the execution of the Salt Spray Test. The test was performed in accordance with the specification ASTM B117 [9] and the assessment of the corrosion damage of each welded specimen was executed in accordance with the specification ASTM G1 [12].

All three welded steel specimens with optimum weld quality, which had the same edge preparation (i.e. single V – butt joint preparation) and the same thickness (i.e. 15 mm), were positioned in the salt spray chamber with the aid of a special welded plastic (PVC) fixture at an angle of 45° such that the unencumbered exposure to the fog is permitted. The exposed areas of the specimens were the weld face and the parent material. The contact between the three welded specimens was avoided and the salt solution from the one specimen did not drip on any other specimen [10]. During the execution of the Salt Spray Test a solution of 5% sodium chloride (NaCl) was used to create a highly corrosive environment in accordance with the specification ASTM B117 [9]. The exposure period of the welded specimens in the salt spray chamber was 300 hours and the temperature was maintained at 35° C (95° F). After 24, 48, 72, 96, 168, 192, 216, 240 and 264 hours of the controlled corrosive environment exposure the mass (gr) of each welded specimen was measured without removing the salt deposits. After 300 hours of the controlled corrosive environment exposure the welded specimens were properly washed in clean running water not warmer than 38°C (100° F) such that the salt spray deposits and the corrosion products were removed from their surface and immediately dried in accordance with the specification ASTM B117 [10].

Afterwards, the mass loss of corroded material and the corrosion rate of each welded specimen were calculated in accordance with the specification ASTM G1 [12] and finally the corrosion morphology of each welded specimen was further analysed with the aid of Optical Microscopy and Scanning Electron Microscopy (SEM). The metallographic analysis was carried out on transverse cross sections properly prepared from all the examined specimens. Standard metallographic techniques (including grinding and polishing) were applied, followed by etching that was Nital 5% for the S355J2+N steel and the HY 100 steel, and Marbles reagent for the 316Ti steel.

3. Results and discussion

The presentation and discussion of the results which came from the experimental investigation of the corrosion resistance of the three steel specimens welded with the optimum welding parameters is included in this chapter:

3.1. Calculation of mass loss each welded steel specimen

The mass measurements of each welded steel specimen after 24, 48, 72, 96, 168, 192, 216, 240 and 264 hours of the controlled corrosive environment exposure are presented in table 2.

After the integration of the Salt Spray Test, the mass loss of each welded specimen, which was calculated in accordance with the requirements of the specification ASTM G1 [12], is presented in table 3. The negligent increase in mass of the 316Ti welded steel specimens is attributed to the fact that an amount of corrosion products was trapped within the exfoliated regions and remained despite the cleaning process followed.

Table 2. Mass measurements of each welded steel specimen

Exposure period (hours)	HY 100 welded steel specimen (gr)	S355J2+N welded steel specimen (gr)	316Ti welded steel specimen (gr)
0	7298	6281	7555
24	7301	6284	7556
48	7303	6287	7556
72	7305	6290	7557
96	7310	6305	7556
168	7313	6307	7557
192	7318	6309	7557
216	7319	6314	7557
240	7322	6318	7557
264	7326	6320	7557
After 300 hours exposure and removal of corrosion products	7264	6218	7556

Table 3. Mass loss of each welded specimen after the integration of the Salt Spray Test

Mass loss	HY 100 welded steel specimen (gr)	S355J2+N welded steel specimen (gr)	316Ti welded steel specimen (gr)
Initial mass before exposure (W_1)	7298	6281	7555
Mass after 300 hours exposure and removal of corrosion products (W_2)	7264	6218	7556
Mass loss (W1 – W2)	34	63	negligible

The mass measurements of each welded steel specimen without removing the salt deposits at specific periods of exposure is illustrated below (see Fig.2,3,4).

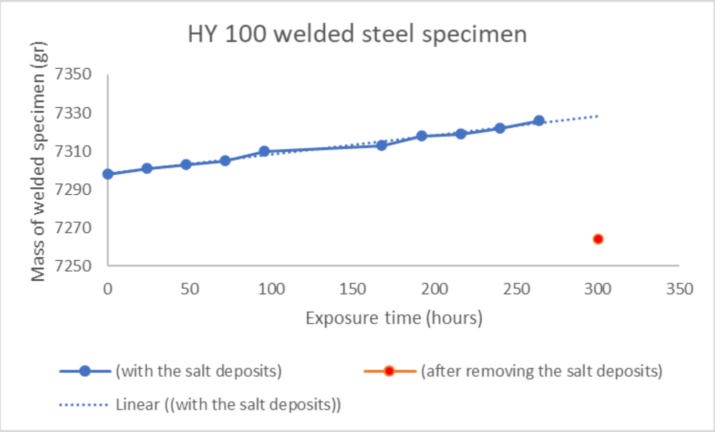

Fig. 2. Mass measurements of HY 100 welded steel specimen at specific periods of exposure

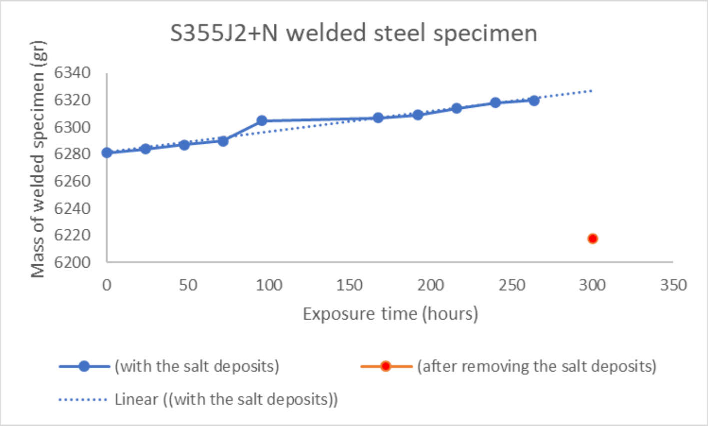

Fig. 3. Mass measurements of S355J2+N welded steel specimen at specific periods of exposure

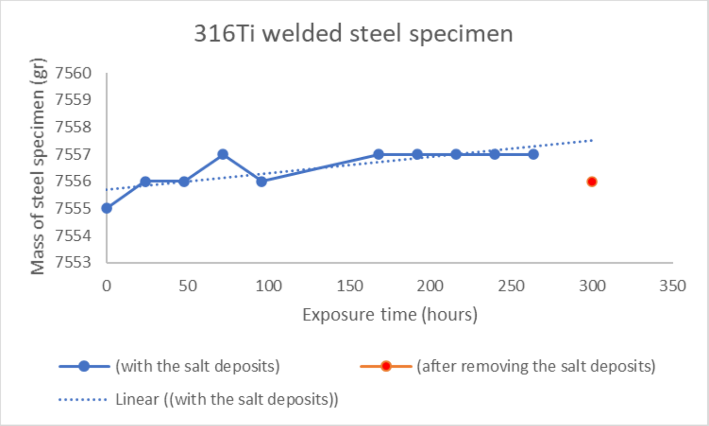

Fig. 4. Mass measurements of 316Ti welded steel specimen at specific periods of exposure

After the integration of the Salt Spray Test, it is obvious from table 3 and from figures 2, 3 and 4 that there is a relationship between the mass values and the period of exposure for each welded specimen. The 316Ti welded steel specimen did not present mass loss because the chemical composition of this material provides very high corrosion resistance to corrosion and oxidation [4].

3.2. Microscopic examination of the surfaces of the welded specimens after the integration of Salt Spray Test

Microscopic examination of each welded steel specimen under examination was executed with the aid of optical microscope and Scanning Electron Microscope (SEM) for the assessment of the corrosion morphology after the calculation of the relative mass loses and the relative outputs are presented for each case:

- The HY 100 welded steel specimen illustrated pitting corrosion (see Fig. 5). The maximum pit depth was measured 40 – 50 μm observed in the weld zone. SEM/EDS analysis was conducted within the pits and representative results are depicted in Fig. 6 and table 4. This analysis indicated that the corrosion products are oxides, while some Cl remained despite the cleaning process executed after the integration of the Salt Spray Test.
- The S355J2+N welded steel specimen exhibited pitting corrosion (see Fig. 7). The pitting corrosion is characterized by deeper pits up to 100 μm. The deeper pits were located at the weld metal.
- The X6CrNiMo17-12-2 (316Ti) austenitic stainless welded steel specimen is characterized by exfoliation corrosion on the weld metal (see Fig. 8). The penetration depth of the corrosion is approximately 25 μm. Corrosion front evolves preferentially via the ferrite phase. SEM/EDS analysis was carried out at selected areas, with corrosion

evidence. Typical results are depicted in Fig. 9 and table 5. The corrosion products are oxides, while significant presence of Cl was detected even after the cleaning process performed after the completion of the Salt Spray Test.

The low mass losses for all specimens under investigation, is attributed to the welding process employed for their manufacturing (robotic FCAW).

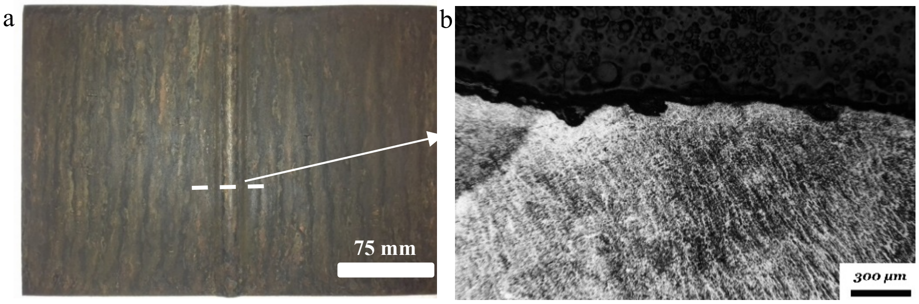

Fig. 5. HY 100**:** (a) Specimen surface after salt spray test. Dash line indicates the area of the metallographic examination on transverse cross section; (b) Morphology of pitting corrosion at the weld metal

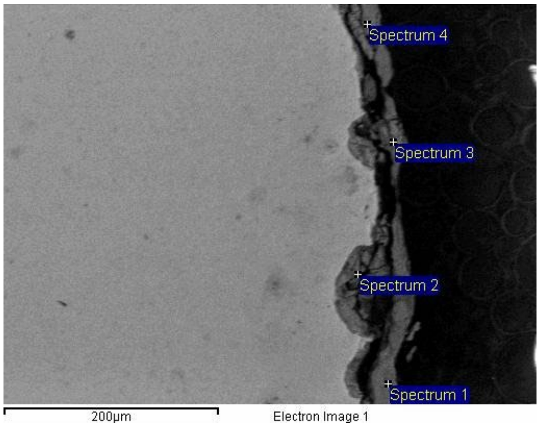

Fig. 6. HY 100**:** SEM image at the corroded area, located at the face of the weld metal.

Table 4. HY 100: EDS semi-quantitative analysis of the corrosion products accumulated within the pits (wt %)

Spectrum (see Fig. 6)	O	Mg	Si	Cl	Cr	Fe	Mo
Spectrum 1	50.27	---	---	2.71	---	47.02	---
Spectrum 2	44.86	---	1.20	---	---	53.94	---
Spectrum 3	51.63	---	0.37	0.19	0.71	47.09	---
Spectrum 4	50.61	0.26	---	0.74	0.49	47.25	0.65

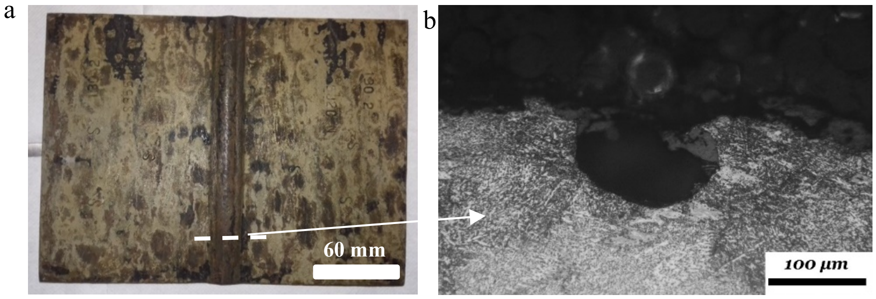

Fig. 7. S355J2+N: (a) Specimen surface after salt spray test. Dash line indicates the area of the metallographic examination on transverse cross section; (b) Morphology of pitting corrosion at the weld metal

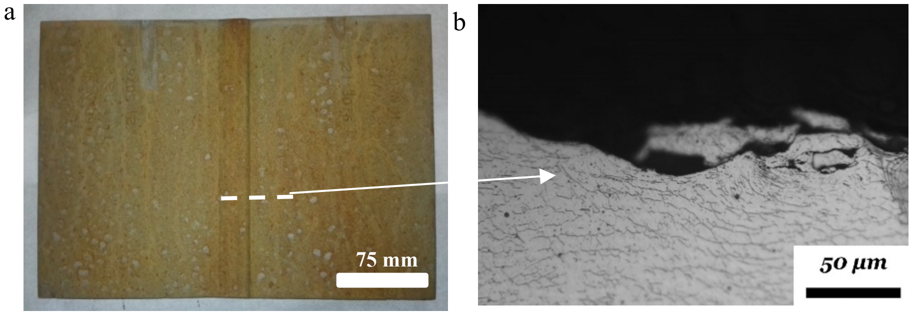

Fig. 8. 316Ti: (a) Specimen surface after salt spray test. Dash line indicates the area of the metallographic examination on transverse cross section; (b) Morphology of exfoliation corrosion at the weld metal

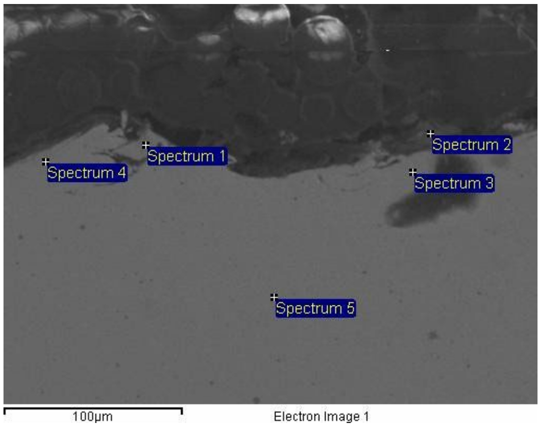

Fig. 9. 316Ti: SEM image of the corroded area located at the face of the weld metal.

Table 5. 316Ti: EDS semi-quantitative analysis of the corrosion products accumulated within the pits (wt %)

Spectrum (see Fig. 9)	O	Si	Cl	Cr	Fe	Ni	Mo
Spectrum 1	---	0.88	---	20.82	64.30	9.55	4.44
Spectrum 2	64.05	---	12.89	5.83	17.24	---	---
Spectrum 3	---	1.39	---	20.95	64.51	10.25	2.90
Spectrum 4	---	0.92	---	18.76	64.81	12.53	2.98
Spectrum 5	---	1.45	---	22.19	61.85	12.60	1.91

3.3. Determination of corrosion resistance of the welded steel specimens under examination

The corrosion rate of the welded steel specimens under examination was determined by the following equation [11]:

$$\text{Corrosion Rate} = \frac{\text{K} \cdot \text{W}}{\text{A} \cdot \text{T} \cdot \text{D}} \tag{1}$$

Where:
K = a constant
T = time of exposure in hours
A = area in cm^2
W = mass loss in grams, and
D = density in g/cm^3

Table 6 illustrates the values of the corrosion rates of the HY100 welded steel specimen and the S355J2+N welded steel specimen. The HY 100 welded steel specimen illustrated higher corrosion resistance than the S355J2+N welded steel specimen.

Table 6. Corrosion rate of each welded specimen after the integration of the Salt Spray Test

Welded steel specimen	Corrosion rate (mm/year)
HY 100 welded steel specimen	0.884
S355J2+N welded steel specimen	1.949

4. Conclusions

The selection of the Salt Spray test was very advantageous for the determination of the corrosion resistance of the three welded specimens probably due to the fact that this method provides the relative results in an accelerated way. Additionally, the optical microscope and SEM analysis of each welded specimen provided very conclusive results about the corrosion morphology. Differences in the corrosion resistance were observed between the weld metal of the HY 100 and S355HJ2N welded specimens. The depth of the pitting corrosion is lower in the weld metal of the HY 100 welded steel specimen than the one in the weld metal of the S355J2+N welded steel specimen. SEM/EDS analysis illustrated that despite the cleaning process performed after the completion of the Salt Spray test, a significant amount of Cl was trapped in the face of the weld metal of 316Ti welded steel specimen, while some amount of Cl was trapped in the face of the weld metal of HY 100 welded steel specimen. The 316Ti welded steel specimen illustrated the highest corrosion resistance, whereas the S355J2+N welded steel specimen illustrated the lowest corrosion resistance. The corrosion resistance of the parent metal is affected by the chemical composition and the properties of the steels under examination. The corrosion resistance of the weldments is affected by the selection and application of the relative welding process. The selection of the FCAW process (compared with other processes) for the welding execution illustrated that many metallurgical, mechanical and corrosion resistant advantages can be gained from the existence of the additional alloys which are included in the flux cored wire and, consequently, can improve the corrosion resistance of the welds.

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