Influence of marine corrosion on the roughness of the dry hyperbaric underwater MAG welding joints

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Abstract. The maintenance and repairing actions for underwater metallic structures from maritime and offshore field are usually achieved using the gas metal arc welding processes. The welding processes applied should take into consideration different underwater conditions, and experiments should be conducted for different pressures. In the first part of the study, the authors focused on the investigation of the EH 36 shipbuilding steel behaviour subjected to dry hyperbaric metal active gas (MAG) using semi-automatic welding devices. Hereinafter, the authors analyse, by using the electrochemical method, the behaviour of the welded joints to marine corrosion. In the last part of the investigation, the corrosion influence on the roughness of the specimen’s surfaces, depending on the potentiodynamic polarization curves, is approached. The experiments revealed that increasing of pressure conditions leads to an increased corrosion resistance and moreover, to a decrease of the specimen surfaces roughness.

1. Introduction

Given the increased interest in underwater interventions for the construction, maintenance, and repair of sunken metal constructions of particular importance (ships, underwater pipes, offshore drilling rigs, hydropower and hydrotechnical structures etc), underwater welding works is one of the basic solutions to be used. The subassemblies from maritime, offshore as well as in the chemical industry are subjected to rough conditions caused by corrosive environments and abrasive particles [1].

Executing underwater welded joints of high quality require specific welding technologies for underwater operations which need specialized, mechanized, and automated equipment which could, in some cases, facilitate the execution of works without the help of scuba divers. Underwater welding operations are carried out in a gaseous environment (protected from water), which is dry welding, or by direct contact with the water, which is wet welding [2], [3]. Beginning from the possibilities of obtaining the welds in accordance with the technical requirements for the field of shipbuilding, five working techniques are known: arc welding in water (wet welding); with local drying; dry hyperbaric in a mini-habitat; dry hyperbaric, and dry at atmospheric pressure [4], [5].

In case of underwater interventions, dry hyperbaric welding ensures a welded joint quality close to the joints made in atmospheric conditions. The created dry environment allows the preparation for the welding procedure, the actual welding of the joints, the non-destructive testing, as well as applying the anti-corrosion protection. Important attention should be paid to the preparation of the joint’s surface, for applying the primer and the anticorrosive paint. In this study, the authors present an experimental
program that investigates the welding behavior of EH 36 naval steel with 14 mm thickness. The purpose and novelty of the current investigation is to study the underwater hyperbaric welding technology using different pressures and to evaluate the corrosion behavior by electrochemical method, and the influence of the marine corrosion on the surface’s roughness of welded joints.

2. Materials and methods

2.1. Welding materials and equipment
Within the experimental program, the following materials and equipment were used [2]: six EH 36 naval steel sheets with the dimensions of 500x150x14 mm; cored with E70C-6MH4 eco-friendly metal powder and the diameter of 1.2 mm; M21 active shielding gas mixture (82% Ar + 18% CO₂); flat ceramic backing with concave channel (channel width 10 mm and channel depth 1.3 mm); dry hyperbaric underwater welding simulator equipped with Aristo Lud 320 universal welding power source and Railtrac FW 1000 welding tractor.

2.2. Welding of samples
Within the experimental program, a number of three butt welded samples were done, on the flat ceramic backing, at atmospheric pressure (P0) and at overpressures in the pressurized chamber of 2 bar (P2) and at 4 bar (P4) in the vertical ascending position. In table 1, the main welding parameters (I - amperage; U - voltage; \(v_p\) - speed of the welding tractor; \(w_f\) - wire feed speed; \(L_p\) - oscillation amplitude; \(\beta\) - welding gun tilt angle; \(w_s\) - welding speed; \(Q\) - heat input) of the dry hyperbaric underwater welding regimes on the flat ceramic backing with E70C6MH4 eco-friendly metal powder cored wire are presented, according to the working pressure in the pressurized chamber [6]. In the case of the P2 and P4 welded samples, for removing the compressed air from the arc welding area, the M21 shielding gas mixture was administered at the overpressures of 7 bar and 9 bar.

![Figure 1. Underwater and hyperbaric welding simulator [5].](image)

The preparation for welding the samples was in V, with a narrow joint (\(\alpha = 40^\circ\)) and the opening of the joint of 6 mm. In figure 1, the underwater and hyperbaric welding simulator is presented (a-simulator; b-welding preparation; c-welding samples) [5]. During the welding of the three samples, a part of the welding parameters were constant [2]: DC+ reverse polarity; pendulum speed \(v_p = 5\, \text{mm/s}\); stop time on the edges \(t_s = 0.5s\); shielding gas flow \(Q_g = 18l/\text{min}\); pre-gas time \(t_{preg} = 3s\); post-gas time \(t_{posg} = 3s\) and the nozzle-layer distance deposited \(h_{d,e} = 15\, \text{mm}\).
Table 1. Variable technological parameters of welding regimes [5].

| No. of sample | Working pressure [bar] | Layer type | \( I_w \) [A] | \( U_s \) [V] | \( v_t \) [cm/min] | \( w_s \) [m/min] | \( L_p \) [mm] | \( \beta \) [°] | \( w_s \) [mm/s] | \( Q_l \) [KJ/mm] |
|---------------|------------------------|------------|----------------|--------------|-----------------|----------------|----------------|--------------|----------------|----------------|
| P0 0          | root                   | 100        | 25             | 10           | 3               | 5              | +10            | 0.7           | 2.9            | 100            | 25             | 3              | 10             | 2.9            | 100            | 25             | 3              | 10             | 2.9            | 100            | 25             | 3              | 10             | 2.9            |
|               | filling                | 100        | 25             | 20           | 1              | 10             | -10            | 1.7           | 1.2            | 100            | 25             | 25             | 3              | 20             | -10            | 2.0           | 1.0            | 100            | 25             | 3              | 20             | -10            | 2.0           | 1.0            |
|               | cover                  | 20         | -10            | 2.0          | 1.0            | 20             | -10            | 2.0           | 1.0            | 20             | -10            | 2.0           | 1.0            | 20             | -10            | 2.0           | 1.0            |
| P2 2          | root                   | 80         | 31             | 10           | 3               | 5              | +10            | 0.7           | 2.8            | 80             | 31             | 20             | 3              | 10             | -10            | 1.7           | 1.2            | 80             | 31             | 25             | 3              | 20             | -10            | 2.0           | 1.0            |
|               | filling                | 80         | 31             | 20           | 3              | 10             | -10            | 1.7           | 1.2            | 80             | 31             | 25             | 3              | 20             | -10            | 2.0           | 1.0            | 80             | 31             | 25             | 3              | 20             | -10            | 2.0           | 1.0            |
|               | cover                  | 20         | -10            | 2.0          | 1.0            | 80             | 32             | 10             | 3              | 80             | 32             | 20             | 3              | 10             | -10            | 1.7           | 1.2            | 80             | 32             | 25             | 3              | 20             | -10            | 2.0           | 1.0            |
| P4 4          | root                   | 80         | 32             | 10           | 3              | 5              | +10            | 0.7           | 2.9            | 80             | 32             | 20             | 3              | 10             | -10            | 1.7           | 1.2            | 80             | 32             | 25             | 3              | 20             | -10            | 2.0           | 1.0            |
|               | filling                | 80         | 32             | 20           | 3              | 10             | -10            | 1.7           | 1.2            | 80             | 32             | 25             | 3              | 20             | -10            | 2.0           | 1.0            | 80             | 32             | 25             | 3              | 20             | -10            | 2.0           | 1.0            |
|               | cover                  | 20         | -10            | 2.0          | 1.0            | 80             | 32             | 20             | 3              | 80             | 32             | 25             | 3              | 20             | -10            | 2.0           | 1.0            | 80             | 32             | 25             | 3              | 20             | -10            | 2.0           | 1.0            |

3. Results and discussions

3.1. Non-destructive and destructive testing

According to the rules of the Lloyd’s Register (LR), the three dry hyperbaric underwater butt welded joints were subjected to non-destructive testing-NDT (100% visual and radiographic) [5].

For the destructive testing (DT) of the three butt welded samples with the dimensions of 500x300x14 mm, the following test bars were sampled for the laboratory mechanical tests [8], [9]: 1 sample for the macroscopic and microscopic examinations and the Vickers HV1 microhardness test; 4 samples for the front side bending test, 2 samples for root and face bend test, on a bend former of 40 mm diameter and 180°; 2 samples with the calibrated area for the tensile testing and 9 samples for Charpy V-notch impact testing, at -20°C (3 samples with the V-notch in the centre of the weld-WM, 3 samples with the V-notch on the fusion line and 3 samples with the V-notch in heat affected zone - HAZ, at 2 mm from the fusion line-FL).

The results of DT and NDT (Table 2) revealed that the chosen process parameters are suitable for MAG dry hyperbaric underwater welding, using a combination of eco-friendly cored wire E70C6MH4, M21 gas mixture, and the high strength naval steel EH 36 of 14mm thickness.
Table 2. Results of NDT and DT according Lloyd’s Register (LR).

| Type of test                        | Extension/sample no. | Welded sample | Non-destructive testing | Destructive testing |
|-------------------------------------|----------------------|---------------|-------------------------|---------------------|
|                                     |                      | P0            | P2                      | P4                  |
|                                     |                      |               |                         |                     |
| Visual test                         | 100%                 |               | Accordingly (no surface defects) |                     |
| Radiographic test with gamma radiation | 100%                 |               | Accordingly (no interior defects) |                     |
| Destructive testing                 |                      |               |                         |                     |
| Transverse tensile test             | 2                    | R_p0.2 [MPa] | 399.36                  | 396.61              | 401.85              |
|                                     |                      | R_m [MPa]    | 406.37                  | 408.09              | 402.05              |
|                                     |                      | Elongation [%]| 546.76                  | 544.98              | 544.08              |
|                                     |                      |               | 548.87                  | 549.07              | 542.16              |
|                                     |                      |               | 33.05                   | 33.15               | 33.03               |
|                                     |                      |               | 33.35                   | 33.17               | 33.07               |
| Bending test                        | 4 (bend former of 40 mm diameter, at 180°) |               | Good (no defects)        |                     |
| Charpy V-notch impact test at -20°C |                      | 3- WM         | 41/49/43                 | 42/40/48            | 40/42/46            |
|                                     |                      | 3- FL         | 82/87/87                 | 88/85/82            | 88/73/84            |
|                                     |                      | 3- HAZ        | 109/111/106              | 102/110/105         | 99/92/101           |
| Macroscopic examination             | 1                    | HAZ           | Increased ferrito-perlitic granulation with the relative pressure increasing |                     |
| (Nital 10%)                         |                      | WM            | Acicular ferrite and modified perlite |                     |
| Microscopic examination             |                      |               |                         |                     |
| (Nital 2%)                          | 1                    | HAZ           | Increased Vickers HV1 microhardness in WM and HAZ with relative pressure increasing |                     |
| Vickers HV1 microhardness test      | 1 (3 investigation directions) |               |                         |                     |

3.2. Corrosion behaviour by electrochemical method

The experimental program regarding the corrosion behaviour of the joints welded in seawater, with the characteristics presented in table 3, were carried out with the electrochemical work equipment, schematically presented in Figure 2.a, formed of the PGZ 100 potentiostat/galvanostat (Figure 2.b), the electrochemical cell, and the data acquisition system.

Table 3. Seawater characteristics.

| Pressure, [db] | Sigma-Theta, [Kg/m²] | Salinity, [PSU] | Conductivity, [S/m] |
|---------------|----------------------|----------------|---------------------|
| 10.49         | 8.43                 | 144.73         | 8.90                |

| Oxygen, [mg/l] | pH | ORP, [mV] | SeaTurbMtr, [FTU] |
|---------------|----|-----------|-------------------|
| 5.28          | 10.00 | 15.30    | 2.22              |

The figure presents two images of the electrochemical cell before (Figure 2.c) and after (Figure 2.d) finalizing the corrosion analysis. In the electrochemical cell, containing 200ml natural seawater from the Black Sea, three electrodes were set, work (cathode) WE, auxiliary (anode) Pt-Rd AE, and reference RE.

The way of sampling the working electrodes, from the samples previously subjected to the mechanical testing, is shown in figure 3. The recording and interpreting the experimental research results was performed using the PGZ 100 potentiostat/galvanostat and the VoltaMaster 4 software.
Figure 2. Electrochemical work equipment and the electrochemical cell [6]

Figure 3. Sampling for the corrosion behaviour test [6].

Figure 4. Potentiodynamic polarization curves.

Figure 4 presents the potentiodynamic curves when testing for corrosion in natural seawater of the test bars sampled from the welded joints.

3.3. The influence of marine corrosion on surface roughness

The experimental research regarding the influence of marine corrosion on the surface roughness of the three test bars was done by using the SJ210 Mitutoiu roughmeter and the SJ - Communication - Tool analysis software. The determinations were done on a 4 mm distance with a speed of 0.5 μm/s, on the three test bars’ surfaces, before and after carrying out the corrosion behaviour analyses.

For the dry hyperbaric underwater welded joints at the three pressures, the determinations were carried out in the cover layer of the welded joints. Figure 5 presents the evolution of the roughness depths of the surfaces for the P0, atmospheric pressure, figure 6 for P2 (pressure - 2 bars) and figure 7 for P4 (pressure - 4 bars), before and after performing the corrosion behaviour analysis, related to the cover layers, basically in direct contact with seawater. The measurements were performed in three different areas of the samples on a 4mm length. It can be noticed that the profiles for height asperities is quite similar, the values varies between -8 μm and +8 μm, but a decrease in the arithmetic average of the surfaces roughness ($R_a$) can be observed for P4 sample.
Figure 5. Evolutions of roughness depths for test bar P0.

Figure 6. Evolutions of roughness depths for test bar P2.

Figure 7. Evolutions of roughness depths for test bar P4.

The SJ-Communication-Tool analysis software was used for data acquisition and processing for the average roughness Ra. In the figure 8 it can be noticed the processed data for the average roughness Ra of the welded samples, before and after the corrosion behaviour analysis, for the case of P0, P2 and P4 pressures. It can be observed that by increasing pressure (P4 pressure condition) the average Ra roughness of the samples decreases by 30%.

Figure 8. Average Ra roughness.
4. Conclusions
The analysis of the welded samples subjected to non-destructive and destructive testing from high strength naval steel EH 36 with 14mm thickness reveals that the MAG dry hyperbaric underwater welding technologies can be used for the maintenance and repairing of underwater metallic structures from maritime and offshore field. From the analysis of the potentiodynamic polarization curves of the three welded samples, it can be noticed that increasing the relative pressure inside the pressurized chamber, the corrosion resistance of the welded joints also increases. The roughness of the specimen surfaces, after the corrosion analysis, are higher, due to the corrosive action of the water from the Black Sea. The roughness values of the specimen decreased as the pressure inside the chamber increased.

5. References
[1] Heider B et al. 2020 Corrosion Resistance and Microstructure of Welded Duplex Stainless Steel Surface Layers on Gray Cast Iron Journal of Thermal Spray Technologies 29 pp 825–842
[2] Hu Y, Shi Y, Sun K, Shen X and Wang X 2018 Microstructure and mechanical properties of underwater hyperbaric FCA-welded duplex stainless steel joints Journal of Materials Processing Technology 261 pp 31-38
[3] Miklaszewski A, Jurczyk M U and Jurczyk M 2013 Microstructural Development of Ti–B Alloyed Layer for Hard Tissue Applications Journal of Materials Science & Technology 6 29 pp 565-572
[4] Verma K and Garg H K 2012 Underwater welding-recent trends and future scope International Journal on Emerging Technologies 2 3 pp 115-120
[5] Gheonea M C 2015 Research on dry hyperbaric underwater mechanized MAG welding with ecological cored wire PhD Thesis "Dunarea de Jos" University of Galati
[6] Carpenter K R, Monaghan B J and Norrish J 2009 Analysis of fume formation rate and fume particle composition for Gas Metal Arc Welding (GMAW) of plain carbon steel using different shielding gas compositions ISI J.International 3 49 pp 416-420
[7] Gheonea M C, Mihăilescu D, Florescu S N and Scutelnicu E 2018 Experimental assessment of gases and fumes developed during Gas Metal Arc Welding IOP Conf. Series: Materials Science and Engineering 40 (Constanta: IOP Publishing)
[8] *** 2018 Rules for the manufacture, testing and certification of materials Lloyd’s Register
[9] Gheonea M C, Mihăilescu D and Florescu S N 2018 Research on dry hyperbaric underwater mechanized MAG-M welding with ecological cored wire Book of Abstracts Conference on Material Science & Engineering (Galati) p 49

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