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POLARITY AND DEPTH EFFECTS IN WET WELDING PERFORMANCE USING A NICKEL-BASED TUBULAR WIRE

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Abstract. *The ongoing growth of the Brazilian oil industry has increased interest in underwater welding processes due to the need for marine structure construction and repair. In particular, underwater wet welding enables the production of joints in direct contact with water, reducing costs and operational time. However, hydrostatic pressure and the environment compromise the mechanical properties of the weld. Furthermore, as a manual process, productivity and diver safety are significantly affected. In this context, Underwater Wet Flux-Cored Arc Welding technology has emerged as an alternative for maintenance work in underwater environments. The continuous consumable feed improves productivity and weld bead deposition quality while also offering automation potential, overcoming the challenges of conventional Shielded Metal Arc Welding. This work presents the development of a self-shielded flux-cored wire with 60% nickel by weight. Nickel is a key element in enhancing the mechanical properties of the weld metal, as it reduces the diffusible hydrogen content, thereby minimizing the risk of cold cracking. Weld beads were produced using a constant voltage welding source. A factorial experimental design was adopted, considering two factors at two levels, depth (0.3 m and 30 m) and polarity (direct and inverse). The key results indicated that arc stability deteriorated with increasing depth, especially in Direct polarity. The predictive model for diffusible hydrogen revealed higher values in direct polarity and with increased welding current. Moreover, cross-sectional porosity and oxygen content in the weld metal were higher at 30 m depth. It was concluded that the developed flux-cored wire demonstrated good operational performance as a consumable for wet welding, exhibiting satisfactory weldability and acceptable surface quality in shallow water. Additionally, the diffusible hydrogen content was comparable to that of austenitic consumables reported in literature and lower than that of rutile and basic consumables. Finally, this study suggests further investigation into welding parameters variation to enhance weldability and weld bead quality at greater depths.*

Keywords: *Self-shielded flux-cored wire, diffusible hydrogen, nickel-based, weld bead porosity, austenitic consumable.*

1. INTRODUCTION

Wet welding is a crucial technology for the repair and maintenance of structures in direct contact with water, as it eliminates the need for environmental isolation, unlike dry underwater welding (Castellanos-Gonzalez *et al.*, 2025). This advantage results in lower costs and reduced repair times (Moreno-Uribe *et al.*, 2017). However, the convenience of wet welding introduces operational challenges related to the high concentrations of hydrogen and oxygen dissociated from water molecules, as well as elevated cooling rates and significant instability caused by the intense heat dissipation of the electric arc (Sanchez-Lobo *et al*., 2022).

According to Cisquini *et al.* (2024), the most commonly used technique is the SMAW (Shielded Metal Arc Welding) process, also known as MMA (Manual Metal Arc Welding), which is characterized by the use of coated electrodes consisting of a metallic core and an external coating. This coating provides the necessary protection for the molten pool and the electric arc, enabling the welding to be performed (Modenesi and Moreno-Uribe, 2022). However, each time the electrode is consumed, the diver-welder must replace it, which leads to non-productive time and may introduce variability along the deposited weld bead (Labanowski *et al.*, 2008). For this reason, research has been conducted with the aim of implementing processes that assist underwater wet welding, in order to minimize operational costs and processing times, without compromising the quality and integrity of the welded structures (Moreno-Uribe *et al.,* 2024).

In this context, the FCAW (Flux Cored Arc Welding) process emerges as a promising alternative, with a considerable amount of research and growing acceptance. This method employs a self-shielded, continuous tubular wire, which increases the productivity of repair work while maintaining the quality of the weld bead (Chen *et al.,* 2022). Additionally, the process allows for automation, aiming at its use in greater depths, thereby enhancing the safety and feasibility of maintenance projects (Castellanos-Gonzalez *et al.*, 2024). As explained by Castellanos-Gonzalez *et al.* (2021), similar to the coated electrode, the self-shielded flux-cored wire allows for the addition of elements that modify the characteristics of the arc and the composition of the weld metal. The literature highlights the importance of consumables with nickel additions (Vaccari *et al.*, 2025). According to Li *et al.* (2016), the addition of nickel in the weld metal promotes the stabilization of austenite at room temperature, which contributes to reducing cold cracking. This effect occurs because austenite presents higher hydrogen solubility than ferrite, thereby mitigating the risk of hydrogen-induced cracking during weld bead cooling (Gonçalves, 2016). Moreover, the addition of nickel improves the metallurgical and mechanical properties of the welded joints (Martin *et al.*, 2011). Given these advantages, this study focuses on evaluating how polarity and operational depth influence the performance of a tubular wire containing 60% nickel, aiming to understand its application in underwater repair scenarios.

2. MATERIALS AND METHODS

2.1. SELF-SHIELDED TUBULAR WIRE AND BASE METAL

For all experimental conditions, a 1.6 mm diameter tubular wire was used. The metallic sheath of the tubular wire was manufactured from an SAE 1006 steel strip, 10 mm wide and 0.3 mm thick, using a forming and drawing machine (Fagundes *et al.*, 2018; Moreno-Uribe *et al*., 2025). The chemical composition of the steel strip is presented in Table 1. Additionally, the tubular wire was filled with flux containing 60% nickel. The base metal consisted of ASTM AH36 steel plates, 19 mm thick, a material widely used in naval structures and offshore platforms. The dimensions of the plates and the chemical composition of the base metal are shown in Figure 1 and Table 2, respectively.

Table 1. Chemical composition of SAE 1006 steel strip

Element	**Fe**	**Mn**	**C**	**Al**	**Residual elements**
% By weight	99.5	0.225	0.0557	0.0229	Balance

Table 2. Chemical composition of the base metal

C	**Cr**	**Cu**	**Mn**	**Mo**	**Ni**	**P**	**S**	**Si**	**Fe**
0.16	0.01	0.01	1.41	0.001	0.01	0.016	0.006	0.23	Balance

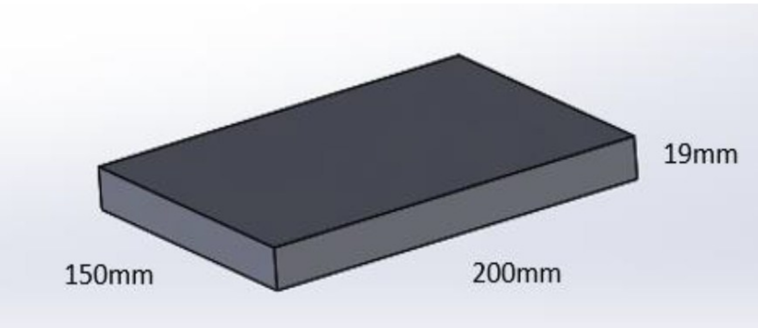

Figure 1. Dimensions of the base metal used

2.2. EXPERIMENTAL METHOD AND EQUIPMENT

The weld beads were deposited in the flat position inside a hyperbaric chamber filled with freshwater, which simulates wet welding conditions at different depths by controlling the ambient pressure through a connection to a compressed air supply line. A uniaxial semi-automatic device was installed in the chamber to assist in adjusting the welding speed, wire feed speed, and to keep the welding torch fixed at a 90° angle relative to the base metal. The welding setup, based on the design described by Assunção and Bracarense (2023), is illustrated in Figure 2. All tests were carried out with fixed parameters, as presented in Table 3, using a constant voltage welding power source.

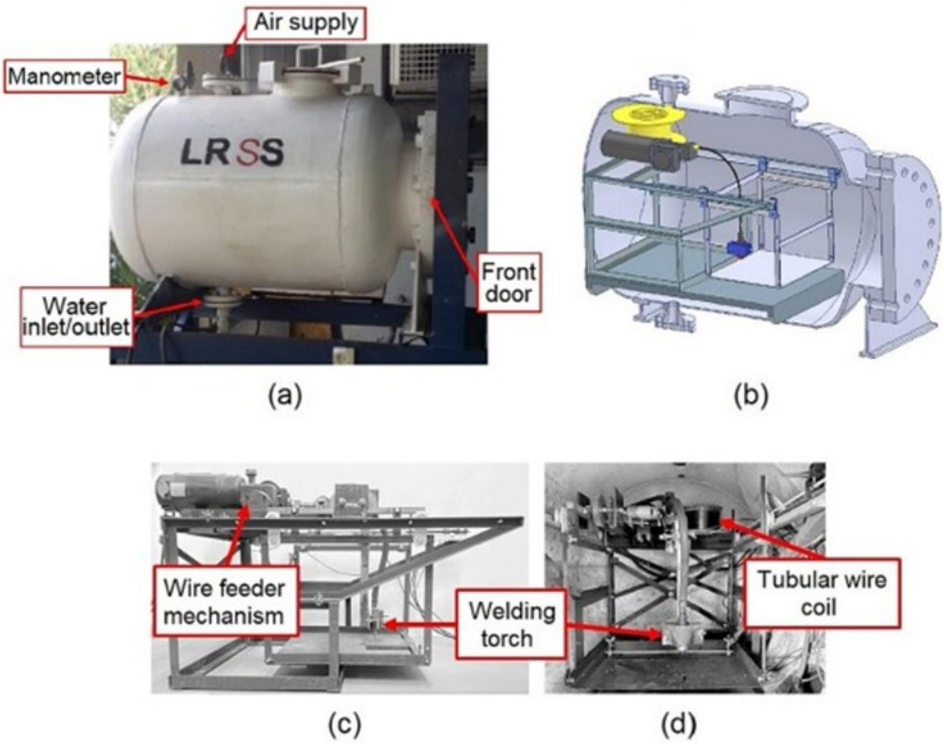

Figure 2. Hyperbaric chamber and mechanism for feeding the tubular wire.
Source: Assunção and Bracarense (2023)

Table 3. Fixed parameters for all experiments.

Arc Voltage	28 V
Wire feed speed	4.4 m/min
Welding speed	25 cm/min
Stick-out	30 mm

2.3. EXPERIMENTAL DATA

2.3.1. ANALYSIS OF ELECTRICAL SIGNALS

The arc voltage and welding current signals were synchronously recorded during the weld bead deposition at a sampling rate of 5000 samples per second, using the SAP V4 acquisition system from *IMC Soldagem*. Subsequently, the signals were processed in the SINAL software, analyzing 8 seconds of the events that occurred 3 seconds after the start of the weld bead deposition. The results included arc voltage, welding current, and standard deviation of the welding current. Additionally, similar to the procedure adopted by Assunção (2018), the proposed index for characterizing arc stability was the coefficient of variation of the welding current, calculated using Eq. (1).

$$KvI\ (\%) = DPI/I \times 100 \quad (1)$$

Where, KvI = Coefficient of variation of the welding current, DPI = standard deviation of the welding current, I = the welding current.

2.3.2. H AND O CONTENT IN WELD METAL

Tests were carried out to determinate the amount of diffusible hydrogen (Hdif) in the weld metal produced under the proposed experimental conditions, with a total of 12 tests performed. The test specimens, 20 mm in length, were dehydrogenated in an electric furnace at 650 °C for one hour. For measuring the diffusible hydrogen content, the gas chromatography method (ASTM E260-96 standard) was applied using the OERLIKON YANACO equipment, model HDM ANALYZER G-1006H. The equipment provides the amount of hydrogen that diffused into the weld metal (H), and the diffusible hydrogen in the deposited weld metal (ml/100 g) is calculated using Eq. (2)

$$\text{Hdif} = \text{H}\,(100) / \Delta M \tag{2}$$

Where, ΔM = mass of deposited weld metal in the specimen (g), obtained from the difference between the specimen's mass after welding and before testing.

For the determination of oxygen content, weld metal samples of approximately 500 mg were collected from the weld bead reinforcement of the specimens used in the diffusible hydrogen tests. Thus, the analysis of the samples was carried out using the inert gas fusion method with an ELTRA ON 900 analyzer. The procedure involves heating the sample in a pulse furnace that can reach temperatures of about 3000 °C. In this process, the sample is melted in a graphite crucible, and the oxygen content is determined by non-dispersive infrared cells.

2.3.3. POROSITY IN THE CROSS-SECTION

To determine the porosity in the cross-section, 10 cm long samples were taken from the center of each weld bead, embedded, and conventionally prepared for metallographic analysis. The porosity percentage was calculated by summing the pore areas and dividing by the total weld bead area, as shown in Eq. (3).

$$\%\ \text{Porosity} = \sum \text{Pore area}/\text{total weld bead area} * 100 \tag{3}$$

2.4. EXPERIMENTAL FACTORS

Table 4 presents the two experimental factors considered in this study and their respective levels. Each treatment was replicated three times to estimate the experimental error, resulting in a total of 12 experiments. ANOVA was performed to assess the effect of changing each factor's level on arc stability, oxygen content in the weld metal, and porosity. A one-way ANOVA was conducted at a 95% confidence level. When significant differences were detected ($p < 0.05$), Tukey's test was applied for multiple group comparisons. A p-value of less than 0.05 indicates a significant influence of the factor on the response variable (Montgomery, 2008). For diffusible hydrogen content, the multiple linear regression methodology proposed by Castellanos-Gonzalez (2024) was applied to identify regressors with a significant effect on the results.

Table 4. Experimental factors and their levels

Factor	High Level	Low Level
Depth (m)	30	0.3
Polarity	DCEP	DCEN

3. RESULTS AND DISCUSSION

Figure 3 shows that depth significantly influences the KvI (p-value < 0.05). When the process is performed at the shallower depth, the mean coefficient of variation of the welding current is 22.8%, increasing to 36.0% at 30 m. Additionally, the mean welding current increases by 36% with greater depth. Arc constriction due to increased hydrostatic pressure reduced the available energy for stable wire tip melting, as the current supplied by the power source became insufficient under the same voltage setting (Castellanos-Gonzalez, 2024; Omajene *et al*., 2014). As a result, process stability deteriorates with increasing depth up to 30 m. Furthermore, the welding power source compensates for these arc voltage fluctuations by adjusting the welding current, leading to an increase in the mean welding current. Figure 4 presents the representative U-I cyclograms for each combination of depth and polarity, illustrating the arc voltage as a function of the welding current. Process stability is assessed by comparing the areas formed by the point clouds. Area I corresponds to the arc extinction region, characterized by voltages between 35–75 V and welding currents below 10 A. Area II represents the stable arc burning region; the smaller this area, the lower the variations in current and voltage, indicating a more stable welding process (Suban and Tusek, 2003). Area III denotes the short-circuit region, defined by voltages below 15 V. Thus, the effect of depth on point dispersion for both polarities is also evident. As depth increases, a larger area is observed in the short-circuit region, along with greater point dispersion in region II, indicating increased instability. Notably, in the DCEN condition at 30 m, point dispersion is particularly pronounced. These findings are consistent with those reported by Moreno-Uribe *et al.* (2020), who observed that, under DCEN polarity, increased hydrostatic pressure affects energy generation.

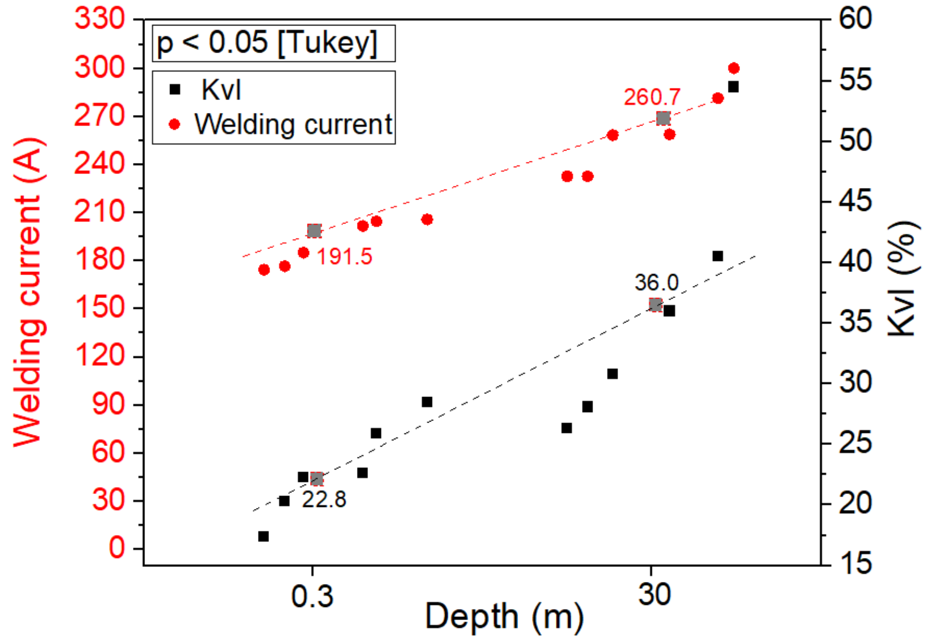

Figure 3. Effect of depth on KvI and welding current

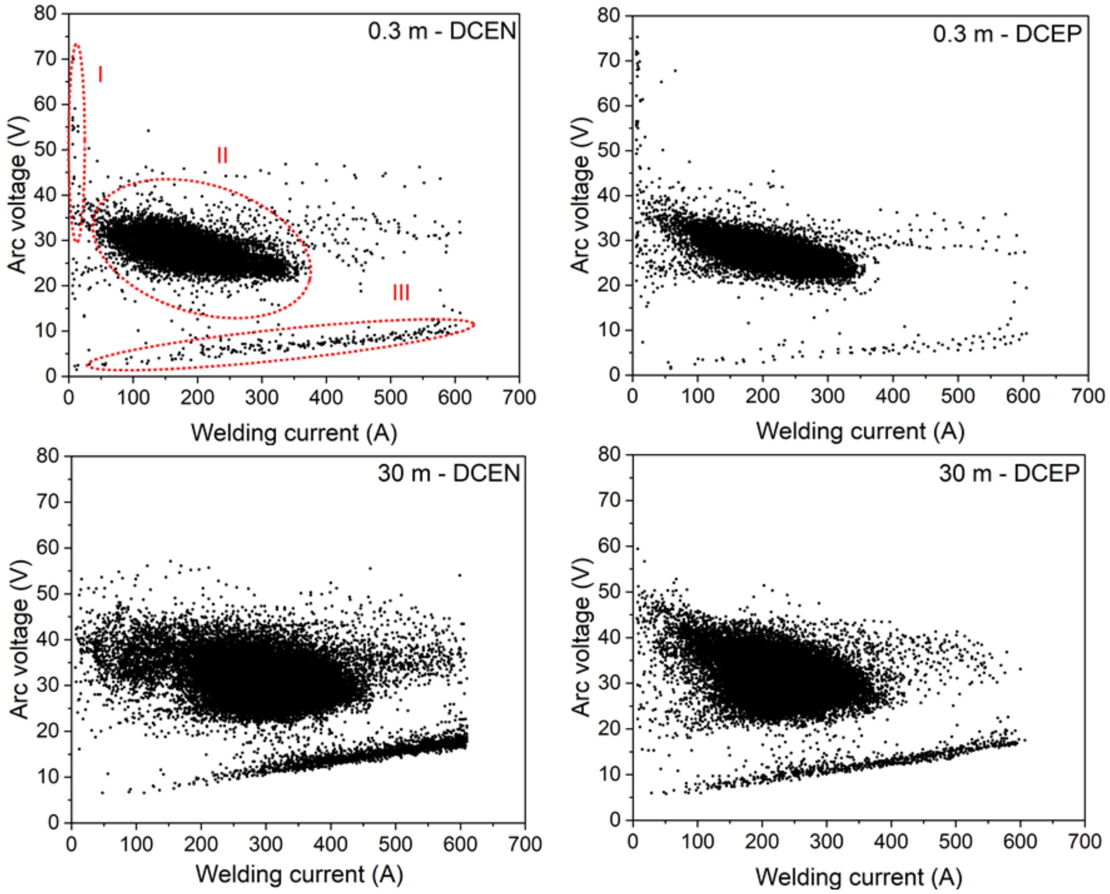

Figure 4. U-I Cyclograms for each depth-polarity combination

Figure 5 shows that the mean weld metal oxygen content increases by 18% at 30 m. Additionally, Figure 6 illustrates that the porosity in the cross-section increased from 0.2% to 17.2% with greater depth. In this context, oxygen absorption in the weld metal changed due to the altered dynamics of metal transfer, which became more unstable at 30 m. Furthermore, the higher number of short circuits with increasing depth is associated with the rise in porosity (Andrade *et al*., 2010). The increase in porosity with depth has also been reported by Suga (1990) and Pessoa *et al.* (2004). Figure 7 shows representative weld beads for each combination of depth and polarity. At 0.3 m, weld beads without surface porosity and with few undercuts are observed, likely associated with the rapid cooling caused by the wet environment. Additionally, similar wettability and good surface quality are evident with both polarities. The figure clearly shows that increasing depth deteriorates the quality of the weld beads, especially with DCEN polarity. This behavior was also reported by Cheng *et al.* (2018), who demonstrated that increased depth impairs the appearance and surface quality of the weld bead.

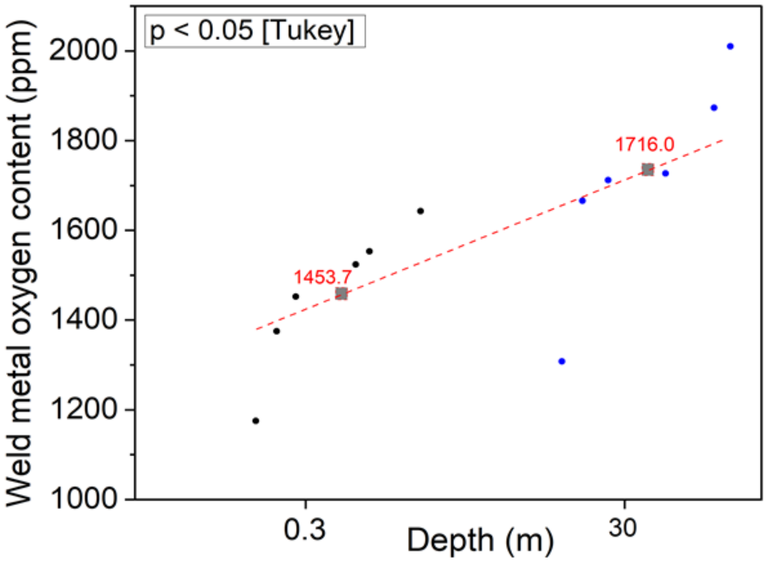

Figure 5. Effect of depth on weld metal oxygen content

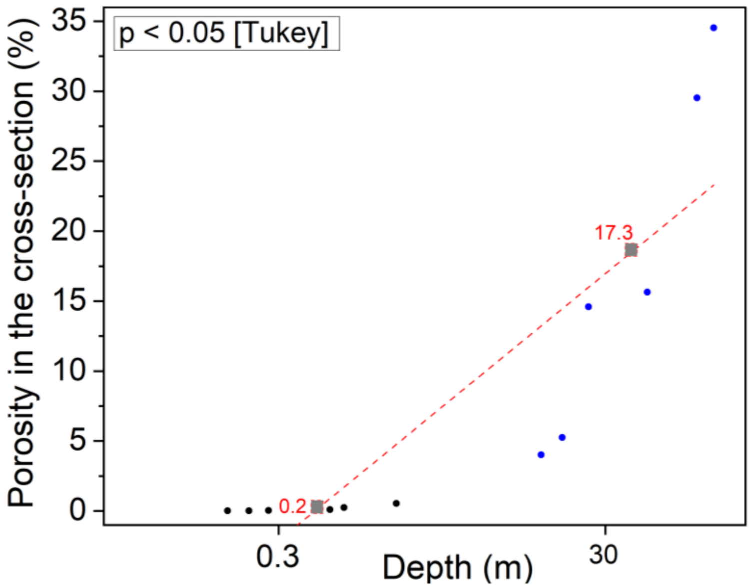

Figure 6. Effect of depth on porosity in the cross-section

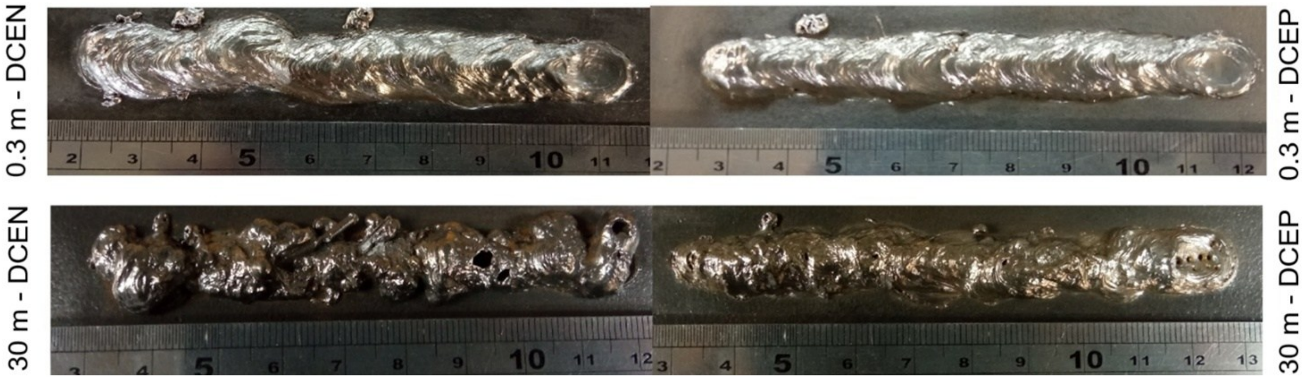

Figure 7. Weld bead quality for each depth-polarity combination

Figure 8 compares the observed and predicted values of diffusible hydrogen obtained from the linear regression model (Eq. 4). Despite the limited sample size—which constrains statistical robustness—the results exhibit a reasonable agreement with the 1:1 reference line (x = y). The model achieved a coefficient of determination of R^2 = 0.807, indicating that approximately 81% of the variability in diffusible hydrogen is explained by the selected predictors. The regression analysis identified polarity as the most influential parameter: switching from DCEN to DCEP results in an average reduction of approximately 8.1 mL/100 g in diffusible hydrogen for the same welding current. In addition, the results indicate that higher welding currents are associated with increased diffusible hydrogen in the weld metal. From a practical standpoint, the model demonstrates potential as a predictive tool for estimating diffusible hydrogen in underwater wet welding, thereby minimizing the need for destructive testing and supporting the optimization of welding parameters for improved operational performance. Although further refinement is warranted, the close agreement between observed and predicted values demonstrates the model's predictive capability and its relevance for engineering applications in underwater environments, specifically for the experimental consumable and the depth and polarity conditions employed in this study.

Table 5 shows the mean diffusible hydrogen values obtained with the tubular wire manufactured in this study, these were lower than those reported by Klett *et al.* (2020) for a rutile-coated electrode at 0.5 m depth (61 mL/100 g), by Ozaki *et al*. (1977) for a basic-coated electrode at 0.3 m depth (51 mL/100 g), and by Da Silva *et al.* (2012) for a rutile-coated electrode at 30 m depth (60.5 mL/100 g). Additionally, the values were comparable to those reported for austenitic electrodes at 0.5 m and 20 m depths (Klett and Hassel, 2020). These results demonstrate that nickel addition represents a viable strategy for reducing diffusible hydrogen, indicating that the electrode composition specifically developed and manufactured in this study has promising applications for repair welding in underwater wet environments.

$$Hdif = 13.64 - 4.053*Polarity + 0.0478*I; \quad R^2 = 0.807 \tag{4}$$

Table 5. Diffusible Hydrogen

Depth	Polarity	Weld metal diffusible hydrogen (mL/100g)	
		Mean	**Standard deviation**
0.3	DCEN	26.3	2.8
0.3	DCEP	18.4	2.0
30	DCEN	31.1	0.3
30	DCEP	22.0	2.3

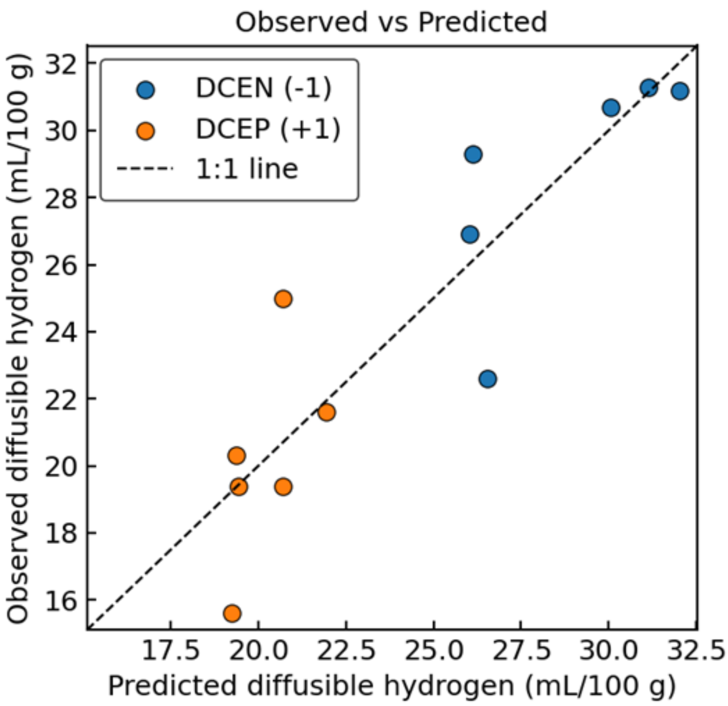

Figure 8. Observed vs. predicted values of weld metal diffusible hydrogen

4. CONCLUSIONS

Based on the experimental results and analyses of process stability, weld metal oxygen content, porosity, and diffusible hydrogen content in underwater wet welding at different depths and polarities, the following conclusions can be drawn:

Process stability deteriorates with increasing depth, as indicated by the rise in the coefficient of variation of the welding current (KvI) from 22.8% at shallow depth to 36.0% at 30 m, and by the greater dispersion observed in the U-I cyclograms, particularly under DCEN polarity.

Hydrostatic pressure at greater depth leads to arc constriction, reducing energy availability for stable wire tip melting and causing the welding power source to compensate by increasing the mean welding current by up to 36%.

Oxygen absorption and porosity increase significantly with depth, with weld metal oxygen content rising by 18% and cross-sectional porosity increasing from 0.2% at shallow depth to 17.2% at 30 m, compromising weld integrity.

Weld bead quality degrades with depth, with more pronounced surface defects and undercuts observed at 30 m, especially under DCEN polarity, confirming that increased depth negatively affects the appearance and structural soundness of the weld bead.

Diffusible hydrogen content was influenced by both polarity and welding current, with higher levels observed under DCEN polarity and at increased welding currents. However, the self-shielded tubular wire developed and manufactured in this study with nickel alloying exhibited significantly lower diffusible hydrogen levels compared to conventional electrodes reported in the literature, confirming its suitability for underwater wet welding applications.

The developed linear regression model for predicting diffusible hydrogen content exhibited a high predictive capability ($R^2 = 0.807$), indicating its potential as a valuable tool for optimizing welding parameters and minimizing the need for extensive destructive testing in underwater welding applications.

5. ACKNOWLEDGEMENTS

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