Influence of the formulation of a flux-cored wire on the microstructure and hardness of welded metal

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Abstract. For this paper, the microstructure and hardness of the weld metal were investigated by conducting experiments with the flux cored arc welding process in underwater and air conditions. A rutile/oxidizing tubular wire was used, manufactured by the Robotics, Welding and Simulation Laboratory at Minas Gerais Federal University, especially for underwater wet welding. Underwater welds had a lower volumetric fraction of acicular ferrite in the weld metal compared to air welds. In the thermally affected zone, for both welds, there was a predominant formation of martensite. However, the grain size and width of the thermally affected zone of underwater welds are smaller. The hardness values shown correspond to the microstructure formed in the weld metal. On the other hand, in the region of the thermally affected zone, the hardness values were higher underwater welds, due to the smaller martensite grains presented.

1. Introduction

The underwater welding technique currently concentrates a large volume of research aimed at developing consumables, equipment, and standards of procedure for industrial applying (Uribe, et al, 2017) [1]. According to Moreno-Uribe, et al. (2020) [2], within the field of underwater wet welding (UWW), the process that has been used the most is shielded metal arc welding (SMAW), due to its characteristics such as versatility and possibility of changing the coating. However, due to its low productivity, which makes repairs more expensive, especially in deep waters, the flux cored arc welding (FCAW) process has been emerging as a promising alternative due to its work-factor, deposition rate and ease of be automated, resulting in high productivity operation, as reported by Amaral, et al. (2021) [3]. Also, other favorable aspect is the presence of flux, a factor that allows changing weld metal characteristics with flux composition variation (Guo, et al, 2016) [4].

However, even with all its potential for use in underwater wet welding, the application of tubular wires has still been limited, as mentioned by Castellanos-González, et al. (2021) [5]. Few studies address the use of this process in underwater wet welding, due to the difficulty in developing consumables and equipment (welding torches) (Assunção and Bracarense, 2017) [6], in understanding and/or combining the characteristics that allow associating its high productivity with adequate mechanical properties of the joint, according to Mendonça and Bracarense (2019) [7].

Thereby, given the promising results obtained by the tubular wires reported by Amaral, et al. (2021) [3], regarding the stability of the electric arc and the reduction of diffusible hydrogen in the weld metal, and considering the growing demand for processes that ensure high productivity in wet underwater welding. This work has as objective the analyses of an experimental
tubular wire, as for application in underwater wet welding; given the reasons mentioned, the present work aims to evaluate the influence of a self-protected tubular wire with a rutile-oxidizing base on the microstructure and hardness of the weld metal.

2. Methodology and materials
The experiments conducted in this work were carried out with a 1.6 mm rutile/oxide self-protected tubular wire developed by the Robotic, Welding and Simulation Lab (LRSS), Brazil, especially for UWW. The flux composition of manufactured wires is summarized below (see Table 1).

| Table 1. Formulation of experimental flux-cored wires (wt %). |
|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Flow | TiO₂ | SiO₂ | Fe₂O₃ | FeSiMn | CaO | FeTi | Iron powder |
| F0 | 35 | 14 | 14 | 12 | 3 | 1 | 21 |

All experiments were carried out at a depth of 0.5 m in a flat position in a tank; during welding, the torch was kept stationary and a welding table with the test specimen moved at a speed of 4 mm.s⁻¹. In this study, an ESAB welding source, model AristoMIG 5001i, in constant voltage mode was used to keep the arc voltage constant during the welding process. The wire feed speed, welding speed and the contact-tip to work distance were fixed. The welding current was automatically changed by the welding power source in order to maintain the pre-set arc voltage and keep the wire feed speed and the fusion rate in the same proportion, as mentioned by Castellanos-González, et al. (2021) [8]. Six weld beads were made for each welding condition (air and underwater condition), with the same welding parameters, resulting 12 weld beads. Table 2 presents the welding parameters used.

| Table 2. Welding parameters. |
|-----------------------------|----------------|
| Voltage | 28 V |
| Wire feed speed | 4.5 m/min |
| Speed of welding | 250 mm/min |
| CTWD* | 30 mm |
| Polarity | DCEP** |

* CTWD: contact-tip to work distance.  
** DCEP: Direct current electrode positive.

Based on the work developed by Moreno-Uribe, et al. (2020) [9] A data acquisition system was used with 5 KHz acquisition frequency, to monitor the welding current, arc voltage and wire feed speed. Figure 1 schematically presents an overview of the entire system necessary for the acquisition of welding data.

![Diagram of welding jig (unscaled).](image-url)
3. Results and discussions
The results of the project show two types of analysis, structural analysis, and hardness analysis.

3.1. Microstructural analysis
To characterize the microstructure, the volumetric fraction of acicular ferrite formed in the weld metal and the other constituents formed was calculated. The methodology used in the analysis was proposed by the International Institute of Welding (IIW) doc. IX-1533-88 [10]. Samples were taken from three different regions of beads deposited on an ASTM A36 steel plate [11]. After the metallographic preparation, the images were obtained with the aid of a CCD camera model Hyper-HAD from the manufacturer Sony coupled to an optical microscope model BX60MF5 from the manufacturer Olympus. For image analysis, Image J software was used. Figure 2 and Figure 3 present the typical microstructures found in the welds of the two welding conditions, in air and UWW, respectively. The microstructures of the top, center, and base of the fused zone and the HAZ of each weld bead are shown.

Figure 2(a) to Figure 2(c) and Figure 3(a) to Figure 3(c), show the formation of different microconstituents in the fused zones of the welds in both welding conditions. The volume fraction of each constituent is shown in Table 3. In the molten zone (see Figure 2(a), Figure 2(b), and Figure 2(c)), it is possible to observe a greater uniformity in the microstructure of the air weld and a predominance of acicular ferrite. In UWW, Figure 3(a), Figure 3(b), Figure 3(c), there is greater heterogeneity in the microstructure and without the massive predominance of a particular constituent. This condition may be linked to the greater number of thermal processes and high cooling rates related to UWW, which influences the reduction of the austenitic grain size.

This result is in line with those presented by Zhang, et al. (2016) [12], where underwaters welds presented a lower proportion of acicular ferrite and pro-eutectoid ferrite compared to air welds, with all welds performed with the same welding parameters and by the FCAW process. In both welding conditions (see Figure 2(d) and Figure 3(d)), the heat affected zone showed a predominance of martensite (M) formation. However, the grain size and ZTA width of underwater welds are smaller (see Figure 3(d)).

![Figure 2](image1.png)

**Figure 2.** Fused zone: (a) top, (b) center and (c) base. HAZ: (d). Composed of acicular ferrite (AF), primary grain boundary ferrite (PF(G)), polygonal intragranular primary ferrite (PF(I)) and aligned second-phase ferrite (FS(A)).
Figure 3. Fused zone: (a) top, (b) center, and (c) base. HAZ: (d). Composed of acicular ferrite (AF), grain boundary primary ferrite (PF(G)), polygonal intragranular primary ferrite (PF(I)), aligned second-phase ferrite (FS(A)) and non-aligned second-phase ferrite (FS(NA)).

Table 3. Volume fraction of the constituents present in the ZF and HAZ.

| Analysis region | Microconstituent | Weld bead |
|-----------------|------------------|-----------|
|                 |                  | Air       | UWW      |
| ZF              | AF               | 46.0 ± 2.0 | 16.5 ± 0.5 |
|                 | PF(G)            | 20.5 ± 1.5 | 22.5 ± 0.5 |
|                 | PF(I)            | 17.0 ± 1.0 | 14 ± 0.0   |
|                 | FS(A)            | 13.0 ± 1.0 | 32 ± 2.0   |
|                 | FS(NA)           | 3.5 ± 0.5  | 15 ± 1.0   |
| HAZ             | M                | 83.5 ± 1.5 | 89.5 ± 0.5 |
|                 | B                | 16.5 ± 1.5 | 10.5 ± 0.5 |

Acicular ferrite (AF), grain boundary primary ferrite (PF(G)), polygonal intragranular primary ferrite (PF(I)), aligned second-phase ferrite (FS(A)) and non-aligned second-phase ferrite (FS(NA)), martensite (M) and bainite (B).

3.2. Hardness analysis

Figure 4 presents the hardness profile, for welding in air and underwater conditions, from the top of the bead to the base metal. It can be observed that the microhardness values obtained for the three regions correspond with the presented microstructures. Air welds had lower hardness in the ZF region, as they presented higher volumetric fractions of the toughest constituent, acicular ferrite, than UWW welds.

On the other hand, in the HAZ region, the two welding conditions have the same constituent, martensite, but in the UWW welds, due to the higher cooling rate, the grains had a smaller size, ensuring greater hardness. The MB region had similar hardness for all conditions due to the use of the same material for all welds.
The results presented for microhardness in the ZF and HAZ of the weld beads in the two welding conditions (air and UWW) are superior to those presented by Zhang et al (2016) [12] also in the two welding conditions. In comparison of microhardness in ZF and HAZ, only for the UWW welding condition, the results are similar to those presented by Gao, et al. (2016) [13].

![Microhardness profile](image)

**Figure 4.** Vickers microhardness profile from HAZ, ZF and MB.

4. Conclusions

In this work, an experimental tubular wire was designed to evaluate the metallurgical characteristics of the weld metal and the heat-affected zone, in air and underwater wet welding. UWW welds had less AF in the molten zone compared to air welds; the HAZ, for both conditions, showed a predominance of martensite, and in the UWW condition, the grain size was apparently smaller.

The results of the Vickers microhardness are in line with the microstructure formed, where due to the smaller volumetric fraction of AF in the molten zone of the UWW welds, the hardness presented a lower value. On the other hand, in the HAZ, the hardness presented high values for both conditions in relation to the molten zone and a slight increase in the hardness of the HAZ in the UWW condition in relation to the air condition.

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