Characterization of an austenitic stainless steel preform deposited by wire arc additive manufacturing

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Received: 15 June 2022 / Accepted: 26 October 2022 / Published online: 10 November 2022
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Abstract
Additive manufacturing (AM) is a fabrication process based on the addition of material by layers and has shown several advantages against other manufacturing processes, such as low cost and possibility of manufacturing parts with complex geometries. However, the additive manufacturing can change the properties of the workpiece due to the strategy of multilayer deposition, which can cause changes in the microstructure of the deposited material. In this sense, this work aimed to evaluate the chemical composition, microstructure, and mechanical and electrochemical behavior of the 316L stainless steel manufactured by wire and arc additive manufacturing (WAAM), comparing it with a sample of the same alloy in the annealed condition, trying to understand how the different layers interfere in the final behavior of the material. The results indicate that the microstructure of the deposited material is different with the presence of ferrite in an austenitic matrix. Two regions whose microstructure had different morphologies were also identified in the WAAM alloy. In the region close to the fusion line between the deposited layers, the austenite grains are smaller, about 5 μm wide, against 10 μm of the grains in the area most to the center of the layers. This microstructural change caused an irregular microhardness profile, with an average of 276 HV, higher than the 190 HV of conventional material. It was also observed that the WAAM process caused a decrease in the yield strength (YS) (23%) and elongation (78%) of the alloy and a slight increase in the value of ultimate tensile strength (UTS) (9%); however, it still meets the minimum requirements for most industrial applications required for the material studied (min. UTS 485 MPa, min. YS 170 MPa, and min. elongation 35 MPa). Moreover, the electrochemical results in simulated seawater solution indicate that the corrosion potential of the deposited sample is like that of the conventional specimen (about 0.24 V), with the potential passivating of the first to be superior to that of the second, respectively, 0.640 V and 0.560 V.

Keywords 316L · WAAM · Microstructure · Mechanical strength · Electrochemistry

1 Introduction
Additive manufacturing (AM) is a fabrication process that consists of creating parts by deposition of material layer by layer. It presents good competitiveness when compared to conventional manufacturing processes, especially in the construction of components with complex geometry, with the advantage of producing almost finished parts, significantly reducing the number of processes to obtain the component in its final form [1–3]. Different types of materials can be used in AM processes, such as metals, which commonly apply techniques that use laser, electron beam, or electric arc as a source of energy [4, 5].

The process known as wire arc additive manufacturing (WAAM) uses the electric arc as a heat source and allows a high deposition rate associated with a low cost, presenting high energy efficiency, and can be applied to various metallic materials [3, 6]. Ozsoy et al. [7] present WAAM as the technique that provides the highest deposition rates in additive manufacturing processes, reaching 2.8 g/s, as reported by DebRoy et al. [4]. According to Singh and Khanna [8], among additive manufacturing techniques, this process ensures better fusion of layers and facilitates the production
of large components (over 10 kg [4]) and low complexity in a shorter period.

Despite the advantages presented, some care must be taken to apply components manufactured by WAAM, since the high energy rate (between 1000 and 3000 W [4]) characteristic of these processes can result in non-homogeneous parts with anisotropic microstructure [9–11]. Balla et al. [12] report the importance of controlling the microstructure of the material, since important properties of crystalline materials, such as mechanical behavior, deformation, and fracture, are strongly influenced by crystallographic orientation and texture. The thermodynamic non-equilibrium that occurs in the complex thermal cycle of wire arc additive manufacturing would be responsible for these changes in the material, since each layer of the deposited material is subjected to different heating and cooling conditions [12–14].

Some authors have presented in their work the influence that the process of additive manufacturing has on the properties of major alloys with great application in the industry [9, 11, 15]. One of these is the 316L stainless steel, object of study of this work, which has vast applications as structural material [15]. Ozsoy et al. [7] report that one of the features that make the AISI 316L alloy attractive to additive manufacturing is its ease of processing. In addition, after processing by WAAM, it presents characteristics similar to those of the welded alloy, thus allowing to use studies on the weldability of this steel [16–19] to predict its behavior.

One of the differences of the 316L alloy produced by WAAM from the conventional is the presence of ferrite in its composition, which may present different morphologies [15, 20, 21]. Chakkravarthy and Jerome [22], Wang et al. [23], and Belotti et al. [24] also report that the wire and arc additive manufacturing generates regions with different microstructures in 316L stainless steel, due to the overlap of layers during the manufacturing process. These changes tend to produce a piece with yield strength and elongation lower than the wrought or annealed AISI 316L alloy, but with a similar yield limit value. Alberti et al. [25] further describe that there is variation in the microhardness of the material, as the microstructure varies, and the highest microhardness values were identified in the regions that were refound and presented higher ferrite concentration and lower grain size.

The microstructural transformations that occurred during WAAM may affect the corrosion resistance of 316L stainless steel, which occurs due to the formation of a passive film of chromium oxide and iron on the surface of the material, with no unanimity among the studies observed in how the wire and arc additive manufacturing interferes with the electrochemical properties of this steel. Chen et al. [21] report that the presence of ferrite in AISI 316L steel has a degrading effect on this passivating layer, with more damage to the alloy when the sigma phase also forms in the material produced by WAAM when immersed in 3.5% NaCl solution. However, Wen et al. [20] when studying the electrochemical behavior of the AISI 316L alloy, also at 3.5% NaCl solution, observed that the deposited workpiece presented lower corrosion rate than the wrought material, with a tendency that the when the heat input in the AM process was lower, the corrosion rate was also lower, and the passivation potential was higher.

Despite the number of published studies on the 316L alloy produced by AM, it was observed that few authors analyzed the application of this stainless steel by arc deposition, with most of the research conducted for laser manufacturing, especially when it comes to the electrochemical behavior of this steel [12, 26–28]. In addition, the workers tend to analyze a rectangular pre-forma in their analyses and as reported by Alberti et al. [25] and Wang et al. [29], the deposition trajectory is a factor that has a great impact on the quality of the workpiece, influencing the stability of the process, the thermal gradient, and the stresses generated by the deposition, directly interfering in the final property of the material.

Thus, attention must be paid to the manufacturing process used in the manufacture of components of this alloy to ensure that, at the end of this, the element has properties suitable for use, such as good mechanical strength and ductility. Among the characteristics of the alloy that can be changed are microstructure, texture, and crystallographic orientation, which among other factors can alter some properties of the material, such as corrosion resistance in certain environments, with a direct relationship with greater susceptibility to localized corrosion [26, 30].

In view of the presented and because WAAM is cheaper than laser processes and for allowing the construction of larger parts [6, 27], this work proposes to evaluate how AM interferes in the microstructure and in the mechanical and electrochemical behavior of the AISI 316L alloy, in order to contribute to the optimization of the process, ensuring greater associated production efficiency. For this, a 316L stainless steel pipe was deposited by wire and arc additive manufacturing and an analysis of the chemical composition, to validate the use of ER316LSi wire to produce an equipment with chemical composition equivalent to AISI 316L steel. Microstructural analysis was also performed, and the phases present in the material in the two manufacturing conditions were also performed with the aim of identifying the changes that could occur due to WAAM. Mechanical and electrochemical behavior of this and an annealed pipe likewise was performed, comparing these results and evaluating the changes that occurred.

## 2 Materials and methods

A pipe with a nominal diameter of 3 inches (Schedule 80 [28]) was manufactured by the wire arc additive manufacturing process. The wire used for deposition was ER316LSi,
whose chemical composition is shown in Table 1, as well as the nominal chemical composition of 316L stainless steel. The AM toolpath was directed by a CAD model that followed a continuous spiral deposition strategy. The deposit was carried out on a substrate with similar chemical composition, resulting in a tube with a length of 200 mm and an average thickness of 11 mm. The parameters used in the process are shown in Table 2. For temperature control during the manufacture of the pipe, the near-immersion active cooling technique was used [31].

The deposited pipe, shown in Fig. 1a, was machined to reduce surface roughness (internal and external) (Fig. 1b). After machining, rectangular plates were removed from the tubes, as shown in Fig. 1c, to remove the specimens. By means of waterjet cutting, circular samples of 13.5 mm in diameter were removed for microstructural analysis (Fig. 1e and f) and specimens for tensile testing, in the transverse direction of the tube, made according to the standard format for subsize tests described in the ASTM E-8 M [32] and visualized in Fig. 1d. For purpose comparison, samples of the same dimensions were taken from a seamless tube, annealed, made of AISI 316L stainless steel, and subjected to the same analysis as those produced by WAAM.

The chemical composition of the components was determined by mass discharge spectrometry (GDS), with LECO GDS500A equipment. To characterize the phases present in the analyzed alloy, an X-ray diffraction test (XRD) was carried out, varying 2θ from 30 to 100° at a rate of 2°/min, with a Shimadzu X-ray diffractometer model XR6000. The identification of the phases was carried out by comparison with the crystallographic charts of the austenite (Fe FCC—face-centered cubic) and ferrite (Fe BCC—body-centered cubic) phases, whose ICSD (Inorganic Crystal Structure Database) values are, respectively, 108,132 and 103,560. The surface preparation of the samples was done by sanding up to 1200 mesh.

For microstructural characterization, images were obtained with a Leica Optical Microscope (OM) model DM750 with a Leica MC120 HD camera connected to a computer to capture the images. For better visualization and definition of the microconstituents present in the samples, images were obtained with a Tescan Scanning Electron Microscope (SEM), LMU model, coupled with EDS, to verify the chemical composition of the microconstituents identified in the specimens. For this, the metallographic preparation of the samples was done by sanding the surface up to 1200 mesh, following for polishing with diamond paste of 1 μm and attack with aqua regia. The determination of some dimensions, such as layer height in the sample deposited by WAAM or grain size, was performed with the help of ImageJ software. This same tool was used to estimate the fraction of ferrite present in the images obtained via SEM of the WAAM specimens.

To assist in the microstructural characterization, based on the chemical composition, the equivalent chrome values (Creq) and equivalent nickel (Nieq), respectively, and Eqs. 1 and 2, were determined to identify the solidification mode of 316L stainless steel by WAAM.

\[
\text{Creq} = \text{Cr} + 2\text{Si} + 1.5\text{Mo} + 5\text{V} + 5.5\text{AI} + 1.75\text{Nb} + 1.5\text{Ti} + 0.75\text{W} \\
\text{Nieq} = \text{Ni} + \text{Co} + 0.5\text{Mn} + 0.3\text{Cu} + 25\text{N} + 30\text{C}
\]

(1) (2)

The mechanical behavior was evaluated from microhardness measurements, performed with a SHIMADZU microhardness tester model HMV-G series 2, with application of a load of 4.9 N (HV 0.5) for 15 s. Measurements were carried out along the entire profile of the sample, in a straight line, in order to verify if there were variations in microhardness along the deposited layers, and the measurements closest to the edge of the samples were discarded. Tensile tests were also carried out on the SHIMADZU machine, model AG–X 300 kN, at a rate of 1 mm/min.

To characterize the electrochemical behavior of the alloy, open circuit potential (OCP) tests were performed until stabilization, followed by the ±0.4 V potential polarization around the OCP with 1 mV/s rate. The tests were performed with Potentiostat/Galvanostat PGSTAT204 and standard three electrodes. The Ag/AgCl electrode was used as reference.

| Table 1 | Nominal chemical composition of 316L stainless steel according to ASTM A312 [33] and ER316LSi metal wire used in the deposition of pipe by WAAM |
|---|---|
| Chemical composition (%) | Cr | Ni | Mo | Mn | Si | C | P |
| Max. ASTM A312 [33] | 18.000 | 14.000 | 3.000 | 2.000 | 1.000 | 0.030 | 0.050 |
| Min. ASTM A312 [33] | 16.000 | 10.000 | 2.000 | - | - | - | - |
| Wire ER316LSi | 18.400 | 12.100 | 2.500 | 1.700 | 0.860 | 0.010 | 0.024 |

| Table 2 | Parameters used in the manufacture of 316L stainless steel pipe by WAAM |
|---|---|
| Number of layers | 120.00 |
| Deposition time (h) | 0.85 |
| Melting rate (kg/h) | 4.09 |
| Deposition rate (kg/h) | 4.03 |
| Deposition yield (%) | 98.50 |
| Monitored deposition energy (average ±σ; J/mm) | 631.00 ± 22.00 |
electrode and super duplex stainless steel as counter electrode. The medium used was synthetic sea water solution, whose preparation followed ASTM D1141 [34] for solution without heavy metals.

3 Results and discussion

3.1 Chemical composition

The results of the chemical composition analyzed by GDS of the conventional and manufactured by WAAM 316L stainless steel are shown in Fig. 2. In terms of global chemical composition, from the data presented, it is possible to observe similarity between the values of the chemical elements in each of the samples, with a subtle elevation in the contents of Cr, Ni, Mo, Mn, and Si in the WAAM specimen. In the observation, in terms of chemical composition, an equivalence of the part deposited with the ER316LSi wire with the AISI 316L alloy was produced by conventional process.

Furthermore, in both manufacturing conditions, the chemical compositions found are in accordance with the nominal chemical composition of the alloy, presented in Table 1. An exception, however, was observed in the chromium content of the conventional material, 3% lower than that the minimum quantity desired for 316L stainless steel. This difference, however, can be considered insignificant and may have occurred due to systematic errors inherent to the test performed to determine the chemical composition.

Among the elements present in the samples, Cr and Ni play an important role in the formation of the passivating layer characteristic of this alloy, which makes austenitic stainless steel more resistant to corrosion. They also act by
increasing the mechanical strength of the alloy and increasing its hardness [35]. Furthermore, the addition of Mo in the material contributes to its repassivation, strengthening its passivating layer and reducing the propagation of pitting [36, 37]. There are still some papers, as presented by Botton [38], which indicate that the molybdenum acts facilitating the formation of the passivation state of steel, since the presence of this element leads to the most positive pit potentials and lower values of critical current density and passivation potential. Thus, as they present similar chemical composition, the passivating layer of the deposited alloy and the conventional alloy must present similar behavior. However, its formation is a complex phenomenon and depends on a number of factors, in addition to chemical composition, such as pretreatment, metal surface composition, electrode potential, polarization time, chemical environment, and temperature [39]. The chemical composition of the alloy also influences its solidification mode, thus causing changes in its mechanical properties. In the case of austenitic stainless steel, a higher concentration of ferritic elements such as chromium, molybdenum, and silicon can promote the formation of ferrite as a primary phase, instead of austenite, which is present in the alloy as a secondary phase [35, 40]. Thus, a higher concentration of these elements, associated with the conditions of the WAAM process, can promote a greater amount of ferrite in the alloy, in addition to greater hardness and greater mechanical strength.

### 3.2 Phases

The spectra obtained by the X-ray diffraction test of 316L stainless steel under conventional conditions and deposited by WAAM are shown in Fig. 3, together with the diffractograms referring to FCC iron (austenite) and BCC iron (ferrite). In both cases, spectra similar to the two forms of iron were identified. However, the ferrite peak identified in the reference material was less intense than that of the specimen produced from WAAM. Considering that the peak intensity is related to the fraction of the phase present in the analyzed sample, it is concluded that the amount of ferrite present in the deposited sample is greater than that in the conventional sample, considering that there are only traces of the ferrite phase in this sample [41]. The most intense peaks of ferrite in the sample deposited by WAAM were expected, since this phase was identified in the microscopic images, as will be seen below. Furthermore, the presence of this microconstituent is commonly reported in the literature in 316L stainless steel parts produced by WAAM [22, 41].

### 3.3 Microstructure

The microstructure of the AISI 316L alloy of the annealed pipe is presented in Fig. 4, observing the twins and polygonal grains of austenite (γ), whose size and shape vary, and can be measured from 16 to 50 μm. This is the equilibrium microstructure of austenitic stainless steels, being formed in slow cooling processes.
cooling conditions [42]. Despite the identification of ferrite in the X-ray diffraction test, the micrographic images performed did not allow observing the presence of this phase in this material, instating that it may be present in low content in conventional alloy, as also observed by Rhouma et al. [43].

A macroscopic image of the 316L stainless steel deposited by WAAM is visualized in Fig. 5a. The fusion lines of the layers formed during deposition are evidenced by means of the yellow horizontal lines in the image (Fig. 5a). A microscopic image of the region between layers 1 and 2 (dashed lines in Fig. 5a) is presented in Fig. 5b. From this, it is verified that the microstructure in the transition region between the layers (highlighted zone between dashed lines as regions 1 and 2) is different from the microstructure of layers 1 and 2. This behavior is due to the different cooling rates that each region is subjected to during the additive manufacturing process, since during deposition, a part of the previously deposited layer ends up being partially resonated when a new layer is deposited [22, 42, 43]. Larger enlargements of the microstructure of layer 1 and the interlayer zone (1–2) are presented in Fig. 6a and b, respectively, allowing to clearly observe the difference between them and how this change occurs abruptly.

From the images presented in Fig. 6a and b, in addition to the austenitic matrix (lighter region), the presence of ferrite (darker region) is perceived in different morphologies. Its presence is favored by the rapid rates of heating and/or cooling of the order of $10^3$ K/s that occur in the WAAM process [4, 44, 45]. Stainless steel under these conditions can solidify in four different ways, as shown in Table 3, and the prediction of this mode of solidification is made based on the $\frac{C_{\text{req}}}{N_{\text{eq}}}$ ration. In type I, only the austenite phase is formed. In modes II and III, there is formation of the ferrite and austenite phase; however, in type II, austenite forms as the primary phase and by means of a eutectic reaction; due to the segregation effect of ferritic elements, ferrite is formed, commonly in the centers of austenitic dendrites. In type III, ferrite is formed as the primary phase and austenite formation takes place at the ferrite/liquid interface, with ferrite solidification in the interdenticle spaces at the end of solidification, thus differentiating the microstructure obtained by this mode of solidification of mode II. On the other hand, in type IV, ferrite is the only resulting phase, with austenite formation after solidification [46, 47].

For the 316L stainless steel sample produced by WAAM, using Eqs. 1 and 2, the $\frac{C_{\text{req}}}{N_{\text{eq}}}$ value obtained is 1.74, which corresponds to solidification mode III (FA). In processes such as welding, this type of solidification is desirable for this alloy, since it can give the material greater resistance to cracking and traction [47, 48]. However, the presence of ferrite may decrease the ductility of the alloy [21, 41]. The morphology of ferrite in this mode of solidification, although difficult to be accurately predicted, is commonly vermicular or lathy.
These forms were identified in some regions of the analyzed material, deposited by WAAM, as can be observed in Fig. 6a and b. The identification of these morphologies was performed by visual analysis, comparing the images made with those available in the literature for 316L stainless steel manufactured by WAAM in studies such as those of Chen et al. [21], Belotti et al. [24], and Wu et al. [11]. However, other ferrite morphologies, such as columnar and globular, were also identified in Fig. 6b. Wang et al. [50] report that despite the prediction of solidification mode III for 316L stainless steel manufactured by WAAM, the refunding zone of the deposited layers presents a higher temperature gradient and higher cooling rate, which can modify the solidification mode, from type FA to AF. Similar behavior was also reported by Belotti et al. [24] who observed the vermicular and lathy morphologies predominantly along the 316L stainless steel part deposited by WAAM; however, at the fusion interface, columnar and globular ferrite structures are perceived.

Thus, as the solidification process of deposited parts begins in the farthest region of the molten pool and as the region higher than the weld bead cools transfers heat towards the already crystallized region, the grains that are formed first remain longer in contact with high temperatures, favoring the growth of these temperatures and allowing part of the ferrite to decompose into austenite [51, 52]. Thus, the region farther from the melting zone has between 7 and 14 μm, while for the microstructure in the fusion line (interlayer 1–2), the spacing between ferrite dendrites can reach 9 μm and has an even smaller size when the ferrite precipitates into globular morphology (4 μm). In addition, it is noted that the distance of the dendrites in 316L stainless steel manufactured via WAAM is less than the size of the polygonal grains of the conventional sample. The different morphologies and variations in grain spacing influence the mechanical behavior of 316L stainless steel produced by WAAM, since the spacing of the primary cells is one of the parameters that has a strong relationship with the characteristics of strength and hardness in the analyzed alloy, as will be discussed later [53].

Also based on the images of Fig. 7a and b, an estimate of the ferrite content present in each region was performed, with the aid of the ImageJ software. The data found indicate 9% of this phase in the layer 1 region and 10% in the interlayer zone 1–2. The values obtained are in accordance with the expected for fused austenitic stainless steels, which according to Pessanha [54] who present between 5 and 20% ferrite. Although there are few studies in the literature in which the authors calculate the ferrite fraction present in the 316L alloy produced by WAAM, Chen et al. [21] and Wen et al. [20] obtained, respectively, 7% and 17% of this phase in preforms with chemical composition equivalent to the alloy in question and using the WAAM technique. Although distinct, these values are within the range presented by Pessanha [54] and allow us to conclude that despite the difficulty in predicting the microstructure and the contents of the phases present in various metal alloys produced by WAAM. It is then noticed that the region of layer 1 (farther from the melting zone) has between 7 and 14 μm, while for the microstructure in the fusion line (interlayer 1–2), the spacing between ferrite dendrites can reach 9 μm and has an even smaller size when the ferrite precipitates into globular morphology (4 μm). In addition, it is noted that the distance of the dendrites in 316L stainless steel manufactured via WAAM is less than the size of the polygonal grains of the conventional sample. The different morphologies and variations in grain spacing influence the mechanical behavior of 316L stainless steel produced by WAAM, since the spacing of the primary cells is one of the parameters that has a strong relationship with the characteristics of strength and hardness in the analyzed alloy, as will be discussed later [53].

![Fig. 6 MO Micrography. a Layer 1. b Interlayer 1–2](image-url)

**Table 3** Mode of solidification and influence of the Cr\textsubscript{eq}/Ni\textsubscript{eq} ratio following the solidification of stainless steels

| Solidification | Solidification mode | Mechanism | Cr\textsubscript{eq}/Ni\textsubscript{eq} ratio |
|----------------|---------------------|-----------|---------------------------------------------|
| Austenitic     | I (A)               | Liq → Liq + γ → γ                           | < 1.38                                      |
| Austenitic-ferritic | II (AF)           | Liq → Liq + γ → Liq + γ + δ → γ + δ        | 1.38–1.50                                   |
| Ferritic-austenitic | III (FA)          | Liq → Liq + δ → Liq + δ + γ → δ + γ        | 1.50–2.00                                   |
| Ferritic       | IV (A)              | Liq → Liq + δ → δ                           | > 2.00                                     |
WAAM, as reported by Örnek [30], from a correct selection of the metal wire and the parameters of the WAAM process, one can obtain a component with ferritic-austenitic structure with a ferrite content within the expected range for the molten material.

The chemical microcomposition analysis by EDS of the alloy studied in the austenitic matrix region and in ferrite grains was performed at the points highlighted in Fig. 8a (conventional), Fig. 8b (WAAM layer 1), and Fig. 8c (WAAM interlayer1-2). In the analysis of the material manufactured by WAAM, point 1 corresponds to the austenite phase and points 2 and 3 to ferrite, already for the conventional material; the three points refer to the austenite phase. The values found are presented in Fig. 9 and allow us to observe that the variation of chemical composition in the conventional sample is small, compared to the WAAM component, since only one phase was identified in the annealed material. In the case of the region of layer 1 and interlayer 1–2, in point 1 (austenite), higher concentrations of austenitizing elements (Ni and Mn) were identified and in points 2 and 3, higher concentrations of ferritizing elements (Cr, Mo and Si). Among the components observed, Cr is mainly responsible for the formation of the passivation layer and Mo has great relevance in strengthening this layer. Thus, these micro-regions with smaller molybdenum compositions may be more susceptible to the rupture of this protective film, favoring the occurrence of some forms of localized corrosion, such as pitting.

### 3.4 Microhardness

From the microhardness tests performed on the samples under the deposited and conventional conditions a box plot graph was elaborated presented in Fig. 10a. The data indicate that the sample manufactured by WAAM has the highest average hardness, of 276 HV, against 190 HV of the conventional material. The increase in hardness can be
attributed to the higher concentration of ferrite in the microstructure of the alloy produced by WAAM and to the smaller grain size \([10, 53]\). The WAAM specimen presents greater variation of the data, with a dispersion 118% higher than the data of the conventional sample. This behavior would be the result of the microstructural variations observed in the alloy manufactured by additive manufacture, derived from the different temperatures and cooling rates that each layer is submitted during the WAAM process. Wu et al. \([11]\) present the microhardness profile of a wall deposited by WAAM of the AISI 316L alloy and report greater stability in the measured values in the regions where there was a greater balance between the heat input and the dissipation, since the heat accumulation affects the microhardness of the analyzed sample, and this region is more favorable to present more uniform microstructure.

The non-uniformity of microhardness measurements can be better visualized from the microhardness profile presented in Fig. 10b. An almost linear behavior is then perceived in the microhardness measurements of the conventional material. In the alloy produced by WAAM, microhardness measurements do not present a pattern of behavior

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**Fig. 9** Chemical microcomposition of ferritic and austenitic grains of conventional 316L stainless steel and by WAAM, in the regions of layer 1 and interlayer 1–2

**Fig. 10** Distribution of the microhardness values of the AISI 316L alloy manufactured by conventional process and deposited by WAAM. a In box plot. b Along the analyzed surface
along the analyzed surface, with significant variation in the values found.

### 3.5 Strain

Figure 11 shows the stress strain curves for the AISI 316L alloy manufactured by conventional process and by WAAM. From the results obtained, the values of the ultimate tensile strength (UTS), yield strength (YS), and elongation of the samples were determined. These data can be found in Table 4, together with the reference values presented in ASTM A312 [33] for seamless, welded, and heavily cold worked austenitic stainless steel pipes. The data presented indicate that the deposited material has lower tensile strength and elongation than the conventional sample. However, it was observed that although lower, the UTS value of the component via WAAM is only 8% lower compared to conventional material, which can be considered a low value, indicating a similarity between the ultimate tensile strengths of the two pipes. A similar result is presented by DebRoy et al. [4] who report that there is [4] a tendency for austenitic stainless steels, when manufactured by different additive manufacturing técnicas, to present UTS close to or even higher than that of the alloy annealed or wrought. Moreover, the values found are higher than those of the ASTM A312 standard [33], concluding that 316L stainless steel has the desirable mechanical properties for several industrial applications [7, 55, 56].

The smaller grain size observed in the WAAM alloy tends to give the material a greater mechanical strength. However, the layered construction strategy, characteristic of additive manufacturing, can accommodate inclusions in interfaces and other defects, such as pores or regions of low densities that will deteriorate the mechanical properties of the manufactured components. Thus, the combination of the two factors may have contributed to its lower mechanical resistance and ductility [21, 23, 53, 57, 58]. However, the smaller grain size is indicated as responsible for the increase in the flow limit of the sample deposited by WAAM, since a greater number of grain contours would block the movements of disagreements, causing the increase in this property of the alloy [14, 57, 58].

### 3.6 Electrochemical behavior

The curves obtained by the potentiodynamic polarization are presented in Fig. 12 and are considered typical curves because they represent the characteristics found in all replicates for each material. Table 5 shows the values of the corrosion density modulus ($J_{\text{corr}}$), corrosion potential ($E_{\text{corr}}$), and passivation potential ($E_{\text{PASS}}$). The samples stabilized at the value of open circuit potential (OCP) around $-0.180$ mV. From the results presented, it is observed that the $E_{\text{corr}}$ values for the material in the two manufacturing conditions are similar and that the polarization curve of the deposited material is shifted to higher corrosion currents compared to conventional material, which may indicate a reduction in corrosion resistance of 316L stainless steel manufactured by WAAM, since lower $E_{\text{corr}}$ values correspond to a lower corrosion rate [20, 59, 60].

For both materials in the active anodic region of the curves, the current density increases with the increase of potential, characterizing a possible anodic dissolution of the metal, in the potential $-0.250$ V for the alloy deposited by WAAM and $-0.275$ V for conventional. Passivation, which consists in the formation of a film, characterized by being very stable and adhered to the surface starts at $-0.240$ V and extends to a potential of $0.400$ V for the material deposited by WAAM, thus characterizing a passivation potential range of 0.640 V. For conventional material, passivation extends from $-0.210$ to 0.350 V, which corresponds to a passivation potential range of 0.560 V.

Thus, despite presenting a higher current density value, the superiority in the value of passivation potential in the WAAM material reflects a more improved passivation process, as also reported by Zhong et al. [57] and Zae et al.

| Table 4 | Strain properties at room temperature of 316L stainless steel manufactured by conventional process and deposited by WAAM |
|---------|-------------------------------------|
|          | Ultimate tensile strength (MPa) | Yield strength (MPa) | Elongation (%) |
| ASTM A312 [20] | Min 485.00 | Min 170.00 | Min 35.00 |
| Conventional | 555.51 | 258.21 | 65.77 |
| WAAM | 508.39 | 338.67 | 36.66 |

![Fig. 11 Strain stress curve of the 316L stainless steel manufactured by conventional process and deposited by WAAM](image)
A similar result was also presented by Wen et al. [20]; according to the authors, the passive film formed in 316L stainless steel samples produced by WAAM would be more stable, indicating a possible greater resistance to pit in solutions of 3.5% NaCl. Ettefagh and Guo [61] also report that this stability of the passivation layer resulting from AM can be improved by annealing, due to the elimination of residual tension, forming a thicker and more stable protective layer on the surface, decreasing the corrosion rate of AM samples compared to conventionally processed material.

After the passivation zone occurs transpassivation, where there is an increase in current density for high values of potentials; this fact may be related to the following factors: the reaction of water decomposition, presence of pitting corrosion, or transpassive dissolution of oxide film and an increase in current density for high values of potentials, which may be related to the following factors: the reaction of water decomposition, presence of pitting corrosion, or transpassive dissolution of oxide film [62, 63].

Considering that electrochemical property is the critical factor in the selection of stainless steels, since one of the main applications of 316L alloy is in environments exposed to the marine atmosphere, making it necessary to have good corrosion resistance, especially at high temperatures [64, 65], it can be concluded that there is great potential for the use of 316L stainless steel produced by WAAM in several sectors of the industry. Further studies need to be done to disseminate these results and increase the reliability of the use of AM in the construction and/or repair of components. Also, doing research is needed to investigate how the presence of different microstructures interferes with the electrochemical performance of the AISI 316L alloy in a simulated seawater solution and how the passivating layer of this alloy behaves.

### 4 Conclusions

From the results obtained from the chemical and microstructural analyses and the mechanical behavior of the 316L stainless steel annealed and manufactured by WAAM, the following can be concluded:

1. The use of ER316LSi wire in the WAAM produces a material with chemical composition similar to that of the alloy produced by conventional processes.
2. The WAAM caused changes in the mode of solidification of the alloy and consequently in its phases. Thus, while the conventional material presented completely austenitic microstructure, with ferrite traces, the sample deposited by WAAM was predominantly solidified in ferritic-austenitic mode.
3. The ferrite presents in the alloy processed by AM presented different morphologies, allowing the classification of two regions: layer and interlayer.
4. The layer region presented 9% ferrite with predominantly vermicular and lathy morphology and grain size around 7 μm to 14 μm. Value lower than the 50 μm observed in the conventional sample. In the interlayer region, 10% of ferrite was identified, which in addition to vermicular and lathy morphologies was presented in the columnar and globular form, with a grain size that reached 4 μm.
5. The smaller grain size and the ferrite concentration contributed to the component deposited by WAAM to present greater microhardness than the conventional alloy, in addition to a greater dispersion in the measured values, which varied between one layer and another as it approached or moved away from the fusion line.
6. Also, it caused a decrease in the tensile strength limit and elongation and in increasing the yield limit in the material processed by AM compared to the annealed material. However, these changes in mechanical behavior did not do harm to the alloy, which still meets the minimum requirements for 316L stainless steel, indicating great potential for application of 316L stainless steel produced by WAAM.

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**Fig. 12**  Polarization curves of the 316L stainless steel manufactured by conventional process and deposited by WAAM in simulated seawater solution

**Table 5**  $J_{\text{corr}}$, $E_{\text{corr}}$, and $E_{\text{PASS}}$ values of 316L stainless steel manufactured by conventional process and deposited by WAAM in simulated seawater solution

| Process   | $J_{\text{corr}}$ (μA·cm$^{-2}$) | $E_{\text{corr}}$ (V) | $E_{\text{PASS}}$ (V) |
|-----------|---------------------------------|-----------------------|-----------------------|
| Conventional | 0.094                           | 0.230                 | 0.560                 |
| WAAM      | 0.284                           | 0.245                 | 0.640                 |
The corrosion potential value of WAAM AISI 316L steel, when immersed in synthetic seawater, resembles that of conventional, under similar conditions. However, there was an increase in current density, which may indicate a lower corrosion resistance of the deposited alloy. However, the greater passivation potential of this may indicate a strengthening of the passivation layer of the process material by AM compared to the annealed alloy. Thus, further studies are needed to understand the behavior of the passivation layer and thus verify whether the manufacturing process caused any significant change in the corrosion resistance of the alloy under certain conditions. In addition, it is necessary to investigate whether the different morphologies identified throughout the sample have different behaviors and may affect the electrochemical behavior of the alloy.

Acknowledgements The authors acknowledge the graduate program of the Faculty of Mechanical Engineering (FEMEC) of the Federal University of Uberlândia (UFU) and to the team of technicians and engineers from the Laprosolda welding laboratory who carried out the construction and machining of the specimens and assisted in the execution of the tests here described.

Author contribution Methodology, L.S., M.S., and D. F.; resources, L. V.; writing of original draft preparation, L.B.; supervision, R. G. and L. V.; writing, review, and editing, L. B., M. S., R. G., and L. V.; project administration, D.F. and L. V.; funding acquisition, D.F. and L. V. All authors have read and agreed to the published version of the manuscript.

Funding This research was funded by the Petróleo Brasil S. A. (Petrobras).

Data availability Not applicable.

Declarations

Conflict of interest The authors declare no conflict of interest.

References

1. Sugavaneswaran M, Jebraaj AV, Kumar MDB, Lokesh K, Rajan AJ (2018) Enhancement of surface characteristics of direct metal laser sintered stainless steel 316L by shot peening. Surfaces and Interfaces 12:31–40. https://doi.org/10.1016/j.surfint.2018.04.010
2. Sun L, Jiang F, Huang R, Yuan D, Guo C (2020) Anisotropic mechanical properties and deformation behavior of low-carbon high-strength steel component fabricated by wire and arc additive manufacturing. Mater Sci Eng, A 787:139514. https://doi.org/10.1016/j.msea.2020.139514
3. Kovalenko O (2019) Evaluation of arc stability and preform geometry aspects in additive manufacturing using the MIG/MAG CMT process with a focus on Ti-6Al-4V alloy. 244p. Ph.D. Thesis. Federal University of Uberlândia, MG, Brazil. https://doi.org/10.14393/ifu.te.2019.629
4. Debroy T, Wei HL, Zabacyk JS, Mukherjee T, Elmer JW, Milewski JO, Beese AM, Wilson-Heid A, De A, Zhang W (2018) Additive manufacturing of metallic components – process, structure and properties. Prog Mater Sci 92:112–224. https://doi.org/10.1016/j.pmatsci.2017.10.001
5. Oliveira JM (2019) Characterization of 316L stainless steel part made by the DMLS process. Course Completion Work (Bachelor of Mechanical Engineering) - Federal Technology University, PR, Brazil
6. Ron T, Levy GK, Dolev O, Leon A, Shirizly A, Aghion E (2019) Environmental behavior of low carbon steel produced by a wire arc additive manufacturing process, Metals (Basel) 9(8). https://doi.org/10.3390/m20100888
7. Ozsoy A, Tureyen EB, Baskan M, Yasa E (2021) Microstructure and mechanical properties of hybrid additive manufactured dissimilar 17–4 PH and 316L stainless steels. Mater Today Commun 28:102561. https://doi.org/10.1016/j.mtcomm.2021.102561
8. Singh SR, Khanna P (2020) Wire arc additive manufacturing (WAAM): a new process to shape engineering materials. Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2020.08.030
9. Rodrigues TA, Duarte V, Avila JA, Santos TG, Miranda RM, Oliveira JP (2019) Wire and arc additive manufacturing of HSLA steel: effect of thermal cycles on microstructure and mechanical properties. Addit Manuf 27:440–450. https://doi.org/10.1016/j.addma.2019.03.029
10. Han L, Lin G, Wang Z, Zhang H, Li F, You L (2010) Study on corrosion resistance of 316L stainless steel welded joint. Rare Metal Mater Eng 39(3):393–396. https://doi.org/10.1875/5372/1060086-0
11. Wu W, Xue J, Wang L, Zhang Z, Hu Y, Dong C (2019) Forming process, microstructure, and mechanical properties of thinned 316L stainless steel using speed-cold-welding additive manufacturing, Metals (Basel), vol. 9. https://doi.org/10.3390/met9010109
12. Balla VK, Dey S, Muthuchamy AA, Janaki Ram GD, Das M, Bandopadhyay A (2018) Laser surface modification of 316L stainless steel. J Biomed Mater Res - Part B Appl Biomater 106(2):569–577. https://doi.org/10.1002/jbm.b.33872
13. Rafieazad M, Ghaffari M, Vahedi Nemani A, Nasiri A (2019) Microstructural evolution and mechanical properties of a low-carbon low-alloy steel produced by wire arc additive manufacturing. Int J Adv Manuf Technol 105 (5–6):2121–2134. https://doi.org/10.1007/s00170-019-04393-8
14. Sander G, Babu AP, Gao X, Jiang D, Birbilis N (2021) On the effect of build orientation and residual stress on the corrosion of 316L stainless steel prepared by selective laser melting. Corros Sci 179. https://doi.org/10.1016/j.corsci.2020.100149
15. Zhang X, Shou Q, Wang K, Peng Y, Ding J, Kong J, Williams S (2019) Study on microstructure and tensile properties of high nitrogen Cr-Mn steel processed by CMT wire and arc additive manufacturing, Mater Des 166:107611. https://doi.org/10.1016/j.matdes.2019.107611
16. AWS, American Welding Society, Welding Handbook: Metals and Their Weldability, vol. 4. 1997
17. AWS, American Welding Society, Welding Handbook - welding science and technology, vol. 1. 2001
18. Moteshakker A, Danaee I (2016) Microstructure and corrosion resistance of dissimilar weld-joints between duplex stainless steel 2205 and austenitic stainless steel 316L. J Mater Sci Technol 32(3):282–290. https://doi.org/10.1016/j.mst.2015.11.021
19. Ramkumar T, Selvakumar M, Narayanasamy P, Begam AA, Mathavan P, Raj AA (2017) Studies on the structural property, mechanical relationships and corrosion behaviour of Inconel 718 and SS 316L dissimilar joints by TIG welding without using activated flux. J Manuf Process 30:290–298. https://doi.org/10.1016/j.jmapro.2017.09.028
20. Wen DX, Long P, Li JJ, Huang L, Zheng ZZ (2019) Effects of linear heat input on microstructure and corrosion behavior of an austenitic stainless steel processed by wire arc additive
manufacturing. Vacuum 173: 109131, 2020. https://doi.org/10.1016/j.vacuum.2019.109131
21. Chen X, Li J, Cheng X, Wang H, Huang Z (2017) Effect of heat treatment on microstructure, mechanical and corrosion properties of austenitic stainless steel 316L using arc additive manufacturing. Mater Sci Eng A 715:307–314, 2018. https://doi.org/10.1016/j.msea.2017.10.002
22. Chakkravarty V, Jerome S (2020) Printability of multilayered SS 316L by wire arc additive manufacturing route with tunable texture. Mater Lett 260. https://doi.org/10.1016/j.matlet.2019.126981
23. Wang L, Xue J, Wang Q (2019) Correlation between arc mode, microstructure, and mechanical properties during wire arc additive manufacturing of 316L stainless steel. Mater Sci Eng, A 751:183–190. https://doi.org/10.1016/j.msea.2019.02.078
24. Belotti LP, Domemlen JAWV, Geers MGD, Goulas C, Ya W, Hoeftnagels JPM (2021) Microstructural characterisation of thick-walled wire arc additively manufactured stainless steel. J Mater Process Technol 299. https://doi.org/10.1016/j.jmatprotec.2021.117373
25. Alberti EA, Silva LJ, Oliveira ASCM (2014) Additive Manufacturing: the role of welding in this window of opportunity. Soldagem & Inspeção 19(2):190–198. https://doi.org/10.1590/0104-9224/si1902.11
26. Bilmes PD, Llorente CL, Méndez CM, Gervasi CA (2009) Microstructure, heat treatment and pitting corrosion of 13CrNiMo plate and weld metals. Corros Sci 51(4):867–881. https://doi.org/10.1016/j.corsci.2009.01.018
27. Sun C, Wang Y, Mcmurtrey MD, Jerred ND, Liu F, Li J (2020) Additive manufacturing for energy: a review. Appl Energy 282(October):2021. https://doi.org/10.1016/j.apenergy.2020.116041
28. ASME, American Society Of Metal Mechanical Engineers, ASME B36.10M - welded and seamless wrought steel pipe, 2004.
29. Wang X, Wang A, Li Y (2019) A sequential path-planning methodology for wire and arc additive manufacturing based on a water-pouring rule. Int J Adv Manuf Technol 103(9–12):3813–3830. https://doi.org/10.1007/s00170-019-03706-1
30. Örnec C (2018) Additive manufacturing – a general corrosion perspective. Corros Eng Sci Technol 53:531–535. https://doi.org/10.1080/14784422.2018.1511327
31. da Silva LJ (2019) Near-immersion active cooling for wire + arc additive manufacturing: from concept to application near-immersion active cooling for wire + arc additive, 140p. Ph.D Thesis, Federal University of Uberlândia, MG, Brazil
32. ASTM International, ASTM E8/E8M-21 Standard test methods for tension testing of metallic materials. (2021) 1–30. https://doi.org/10.1520/E0008
33. ASTM International, ASTM A 312/A 312M-21 standard specification for seamless, welded, and heavily cold worked austenitic stainless steel pipes, (2021) 1–12. https://doi.org/10.1520/A0312
34. ASTM International, ASTM D1141 098 standard practice for the preparation of substitute ocean water I. (1998) 1–3. https://doi.org/10.1520/D1141-98R13.2
35. E. Folkhard, Welding metallurgy of stainless steels, 1st ed. 1988
36. Mesquita TJ, Chauveau E, Mantel M, Kinsman N, Nogueira RP (2013) Influence of Mo alloying on pitting corrosion of stainless steels used as concrete reinforcement, Metallurgy and materials - inox 2010, Ouro Preto, Minas Gerais - Brasil, 66(2):173–178
37. Costa RS, Study of corrosion of AISI 304 in hydrated alcohol fuel (2012) 120p. Ph.D Thesis. Federal University of Campinas, SP, Brazil
38. Botton T (2008) Comparative study of corrosion resistance in acid medium and in containing chloride of stainless steels UNS S44400, UNS S31603 obtained by hot rolling, 160p. Dissertation. University of São Paulo, SP, Brazil
39. Nunes PG (2016) Electrochemical evaluation of stainless steel 304L after various welding processes. Dissertation, Federal University of Grande Dourado, MG, Brazil
40. Padilha AF, Rios PR (2002) Decomposition of austenite in austenitic stainless steels. ISIJ Int 42(4):325–337. https://doi.org/10.2355/isijinternational.42.325
41. Vilchez F, Pineda F, Walczak M, Ramos-Grez J (2020) The effect of laser surface melting of stainless steel grade AISI 316L welded joint on its corrosion performance in molten Solar Salt. Sol Energy Mater Solar Cell 213. https://doi.org/10.1016/j.solmat.2020.110576
42. Yang K, Wang Q, Qu Y, Jiang Y, Bao Y (2020) Microstructure and corrosion resistance of arc additive manufactured 316L stainless steel. J Wuhan Univ Technol Mater Sci Ed 35(5):930–936. https://doi.org/10.1007/s11595-020-2339-9
43. Rhouma AB, Amadou T, Sidhom H, Braham C (2017) Correlation between microstructure and intergranular corrosion behavior of low delta-ferrite content AISI 316L aged in the range 550 e 700 C. J Alloys Compd 708:871–886. https://doi.org/10.1016/j.jallcom.2017.02.273
44. DeLong WT (1975) Ferrite in austenitic stainless steel. Weld Metal – 2, Indian Weld 7(3):75–83
45. Lippold JC, Kotecki DJ (2005) Welding metallurgy and weldability of stainless steels
46. Guilherme LH (2016) Influence of the sigma phase on corrosion in microregions of joints welded by MIG processes of stainless steel AISI 316L. 197p. Thesis, University of São Paulo, SP, Brazil
47. Rajasekhar K, Harendranath CS, Ramam R, Kulkarni SD (1997) Microstructural evolution during solidification of austenitic stainless steel weld metals: a color metallographic and electron microscope analysis study. Mater Charact 38(2):53–65. https://doi.org/10.1016/S1044-5803(97)80024-1
48. Somani CA, Lalwani DI (2019) Experimental study of some mechanical and metallurgical properties of TIG-MIG hybrid welded austenitic stainless steel plates. Mater Today: Proceed 26:644–648. https://doi.org/10.1016/j.matpro.2019.12.253
49. Suutala N, Takalo T, Moisio T (1980) Ferritic-austenitic solidification mode in austenitic stainless steel welds 1:717–725
50. Wang C, Liu TG, Zhi P, Lu YH, Shoji T (2020) Study on microstructure and tensile properties of AISI 316L stainless steel fabricated by CMT wire and arc additive manufacturing. Mater Sci Eng A 796. https://doi.org/10.1016/j.msea.2020.140006
51. Zhong Y, Zheng Z, Li J, Wang C (2021) Fabrication of 316L nuclear nozzles on the main pipeline with large curvature by CMT wire arc additive manufacturing and self-developed slicing algorithm. Mater Sci Eng 820. https://doi.org/10.1016/j.msea.2021.141539
52. P. R. S. Soares, Study of corrosion in different types of steel (2012) 78p. Dissertation, Instituto superior doporto, Portugal.
53. Krakhmalev P, Fredriksson G, Svensson K, Yadroitsev I, Yadroitseva I, Thuander M, Peyng R (2018) Microstructure, Solidification texture, and thermal stability of 316L stainless steel manufactured by laser powder bed fusion pavel. Metals (Basel), 8. https://doi.org/10.3390/met8080643
54. Pessanha EC (2011) Quantification of delta ferrite and evaluation of the microstructure/properties ratio of an austenitic stainless steel 347 welded 108p. Dissertation, State university of northern rio de janeiro Darcy Ribeiro, RJ, Brazil
55. Artaza T, Alberdi A, Murua M, Gororratategi J, Frias J, Puertas G, Melchor MA, Mugica D, Suiárez A (2017) Design and integration of WAAM technology and in situ monitoring system in a gantry machine. Procedia Manufacturing 13:778–785. https://doi.org/10.1016/j.promfg.2017.09.184
56. Duarte VR, Rodrigues TA, Schell N, Miranda RM, Oliveira JP, Santos TG (2020) Hot forging wire and arc additive manufacturing (HF-WAAM). Addit Manuf 35. https://doi.org/10.1016/j.addma.2020.101193
57. Zhong Y, Liu L, Wikman S, Cui D, Shen Z (2016) Intragranular cellular segregation network structure strengthening 316L stainless steel prepared by selective laser melting. J Nucl Mater 470:170–178. https://doi.org/10.1016/j.jnucmat.2015.12.034
58. Zae S, Podgornik B, Mario Š, Tchernychova E (2020) Materials Characterization Quantitative multiscale correlative microstructure analysis of additive manufacturing of stainless steel 316L processed by selective laser melting. Mater Charact 160. https://doi.org/10.1016/j.matchar.2019.110074
59. Kale AB, Kim BK, Kim DI, Castle EG, Reece M, Choi SH (2020) An investigation of the corrosion behavior of 316L stainless steel fabricated by SLM and SPS techniques. Mater Charact 163. https://doi.org/10.1016/j.matchar.2020.110204
60. Ron T, Dolev O, Leon A, Shirizly A, Aghion E (2021) Effect of phase transformation on stress corrosion behavior of additively manufactured austenitic stainless steel produced by directed energy deposition. Materials 14. https://doi.org/10.3390/ma14010055
61. Ettefagh AH, Guo S (2018) Electrochemical behavior of AISI316L stainless steel parts produced by laser-based powder bed fusion process and the effect of post annealing process. Addit Manuf 22:153–156. https://doi.org/10.1016/j.addma.2018.05.014
62. Rebak RB, Kon NE, Cotner JO, Crook P (1999) Passivity and localized corrosion. Electrochem Soc Proceed 473:27–99
63. Hayes J, Gray J, Szmodis A, Orme C (2006) Influence of chromium and molybdenum on the corrosion of nickel-based alloys. Corrosion 62:491–500. https://doi.org/10.5006/1.3279907
64. Covert RA, Tuthill AH (2000) Stainless steels: an introduction to their metallurgy and corrosion resistance, Dairy, food and environmental sanitation, 20:506–517
65. Xin SS, Li MC (2014) Electrochemical corrosion characteristics of type 316L stainless steel in hot concentrated seawater. Corros Sci 81:96–101. https://doi.org/10.1016/j.corsci.2013.12.004

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