Original Article

Influence of post welding heat treatments on sensitization of AISI 347 stainless steel welded joints

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ABSTRACT

Austenitic stainless steels can undergo intergranular corrosion attack in some service conditions and to reduce this possibility, some Ti (AISI 321 SS) and Nb (AISI 347 SS) stabilized austenitic stainless steels are used in extreme conditions, such as oil refineries, thermo electrical and petrochemical plants industrial furnaces operating at high temperatures (between 500 °C and 675 °C). Even these ones, if they do not receive sufficient attention in order to avoid sensitization during manufacture or service, can fail during operation. The manufacture standards prescribe solution heat treatment, but, on the other hand, following solution treatment, stabilization is an optional procedure that is adopted only when requested by the client. After welding stabilized pieces, requirements of solution and stabilization heat treatments can be followed, but not always, because sometimes this procedure can be impossible or doubtful. This work presents the influence of the post weld thermal cycles on the AISI 347 SS, with the purpose of establishing recommendations for the obligatory or optional use of these treatments, as a function of temperatures and other operational conditions. The absence of post welding heat treatment (PWHT) in welded components of AISI 347 SS, either in the base metal (BM) or in the heat affected zone (HAZ) is allowed when the service temperature is lower than 450 °C, since the original stabilization heat treatment in the material avoids the sensitization in the piece, while above 450 °C, the local application of stabilization PWHT is more effective to protect this material.

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1. Introduction

The austenitic Stainless Steels (SS) are susceptible to intergranular corrosion due to impoverishment in chromium on
the regions which are adjacent to grain boundaries, through the precipitation of \( M_{23}C_6 \) carbides, mainly \( M = Cr \), and the susceptibility to intergranular corrosion in austenitic stainless steels can be avoided by limiting their carbon contents or by adding Nb, Ti, V, Zr, Hf, and Ta, with greater affinity with carbon, whose carbides are more stable than those of chromium. At temperatures above 815 °C, these stable MC carbides \( (M = Nb, Ti, \ldots) \) remove carbon from solid solution and prevent the precipitation of \( M_{23}C_6 \) carbides, therefore “stabilizing” these steels [1–3].

Amongst the various challenges involved in the welding of austenitic stainless steels, one of the most important is sensitization [4]. Sensitization is a deleterious phenomenon that occurs in austenitic SS when it is submitted to an increase in temperature such as what happens during welding or operating in the temperature range between 400 °C and 800 °C. This is a well-known phenomenon and consists of carbide precipitation at grain boundaries and chromium depletion in adjacent regions, making the material susceptible to intergranular corrosion [5]. Austenitic welded steels may become sensitized in heat-affected zone (HAZ), which causes localized intergranular corrosion at the weld site, although the cooling rate of the metal can be sufficiently high to avoid carbide precipitation [3].

Standards that consider conditions for wrought austenitic stainless steel piping fittings, such as ASTM A-403 standard [6], prescribe necessarily solution heat treatment above 1000 °C, followed by rapid cooling. However, in concern to stabilization \( (815–870 \text{ °C}) \), this one is considered only a supplementary requirement of the standard. Nevertheless, some technical specifications, related to materials designed for tubes and pipes used for petroleum refining, prescribe that welded joints of AISI 321 SS and AISI 347 SS must be subjected to stabilization heat treatment at proper temperatures, including high carbon grades, during a sufficient time to promote precipitation of the stabilizing elements \( (Ti \) or \( Nb) \). The stabilized stainless steels contain either \( Ti \) (AISI 321 SS) or \( Nb \) (AISI 347 SS), which have stronger affinity with carbon than \( Cr \) and thus result in \( TiC \) or \( NbC \). The formation of \( TiC/NbC \) can help in avoiding chromium impoverishment due to the chromium carbide precipitation and in fact, the sensitization could be controlled [4]. Stabilized austenitic stainless steel such as type AISI 347 SS and AISI 321 SS are widely used in components designed for high temperature applications like nuclear reactors, boilers, superheaters and chemical reactors because of their good resistance to sensitization and creep deformation [7]. Also, for assuring the effectiveness of the stabilizing heat treatment, these steels must be subjected to tests that can detect the susceptibility to intergranular corrosion according to the Practice A of ASTM A-262 standard [8] in a condition corresponding to sensitization at 675 °C for at least 1 h, for example.

Regarding components that can be used up to 600 °C, critical condition for sensitization onset, even for short time periods or local points, such as serpentina of preheating furnaces, for instance, that require welding operations in the work field, the HAZ of the sensitized welded joints can undergo intergranular corrosion damage for some conditions, mainly during operation stop events, thus being necessary an evaluation of the need of PWHT above 800 °C, even when in the welded joint of an AISI 347 SS.

The main aim of the solution heat treatment is the dissolution of the phases precipitated during the thermomechanical processing of the material, as, for instance, the case of \( M_{23}C_6 \) [9]. This heat treatment can eliminate the precipitated phases that arise due to the welding thermal cycle to which the welded joint is subjected, recovering the mechanical properties. Most of the precipitates formed during solidification are dissolved, maintaining the alloying elements in solid solution in the austenitic matrix [10]. The solution heat treatment must be carried out at least 900 °C, since the precipitation of the \( M_{23}C_6 \) carbide can occur between 450 °C and 900 °C, for 1–10 h, but it is recommended between 1035 °C and 1120 °C, followed by rapid cooling, a treatment which is performed in welded joints that are supposed to work at temperatures between 400 °C and 900 °C [9,11–13]. Cooling must be rapid enough to avoid sensitization, thus assuring that all chromium and carbon atoms remain in solid solution in the austenitic matrix, which then remains supersaturated in carbon and free of \( Cr_{23}C_6 \) in the grain boundaries, since this carbide phase is the main reason for intergranular corrosion, which does not occur when the stainless steel remains in the fully solution treated condition [11,14].

Stabilization heat treatment has as purpose the enhancement of resistance to intergranular corrosion. After solution heat treatment, only part of the carbon atoms is linked to other types of atoms in primary phases such as MC, \( M(C,N) \), MN, or \( M_4C_2S_2 \). The remaining part of them remains in solid solution and can precipitate as secondary carbides \( MC \) or \( M_2C_3 \) at lower temperatures, since carbon solubility in austenite at 900 °C is very low [9]. In this context, stabilization promotes the precipitation of all available carbon atoms as MC carbides and thus helping to keep chromium atoms in solid solution during service at high temperatures [15]. This treatment can complete the precipitation process, remove micro stresses near grain boundaries, or cause chromium diffusion to depleted areas [12]. Solution treatment and stabilization are postweld heat treatments specially indicated as postweld heat treatments to multipass welds and to cast components made of stabilized austenitic stainless steels designed to high temperature services (450–800 °C) [16].

This work comprised two main parts: the first one evaluated the influence of the thermal cycles in an AISI 347 SS elbow piece, as well as the microstructural evolution before subjecting them to the different PWHT’s; the second one evaluated the same welded joints after the PWHT’s. The focus of this work is to develop a heat treatment procedure capable of improving the resistance to sensitization corrosion of the AISI 347 SS and the characterization of the microstructural changes associated to these heat treatment as possible tool for explaining this improvement. This knowledge can help to widen the possibility of the application of this material in aggressive conditions related to high temperatures.

In this work hot wire GTAW welding operations were carried out in “elbow” shape pieces of AISI 347 SS and later these ones were subjected to different combinations of solution and/or stabilization PWHT’s, as well as ageing conditions which are prone to sensitization occurrence. In order to evaluate the effects of the exposure of the welded joints, with and without PWHT, to the adverse conditions of intergranular corrosion occurrence, qualitative (Practices A and E of ASTM
A-262 standard [8]) and quantitative (DL-EPR) techniques were applied, with the observation of microstructure, mechanical tests and the determination of degrees of sensitization (DOS) of different regions, mainly in the base metal (BM) and in the heat affected zone (HAZ).

In an assembly of pipes and elbow parts they are joined by welding, in that each component is furnished in the heat treated condition: solution treatment followed by stabilization and in concern to this welded junction, some points need further explanation: i) a study on the need of PWHT’s, in the field, of the whole structure (pipeline) or just in the regions under direct influence of welding, as in the case of HAZ, in order to prevent intergranular corrosion/sensitization; ii) the verification of HAZ regions in the welded joints, where the heat treatments performed in the factory are sufficient for protecting against sensitization, during welding or ageing; iii) observation and checking if the application of a solution treatment followed by stabilization is really necessary, or if it is possible to carry out only a stabilization treatment in order to stabilize again the same region of interest.

From this point of view the main aim of this work was to clarify the influence of PWHT’s on the microstructure and the resistance to intergranular corrosion of the GTA welded joints of AISI 347 SS, mainly in the HAZ and BM regions, in order to propose new options of heat treatment procedures for preventing sensitization occurrence.

2. Materials and methods

In this work three elbow pieces of ASTM A-403 Gr. WP347 (AISI 347 SS) applied in serpentines of petroleum industry furnaces with 203.2 mm diameter and 10.0 mm wall thickness in solution treated and stabilized “as furnished” conditions were analyzed. Automatic GTA welding with AISI 347 SS as filler metal. Sensitization susceptibility was evaluated according to Practices A and E of ASTM A-262 standard [8], and DL-EPR technique.

### 2.1. Materials

Table 1 presents the chemical composition of one of the “as received” elbow sample, that is “in the stabilized condition” or “stabilized by the factory”. Chemical analysis was performed by optical emission spectroscopy in inert atmosphere of argonum with 99.999 % minimum degree of purity (grade 5.0) in the chamber where is electronic excitation of the samples, compared with ASTM A-403 standard [6] information. Additionally, it is shown the chemical composition of the filler metal, according to the certificate and this is compared with the one prescribed as ER 347 Si by the AWS A5.9 standard.

### 2.2. Welding methodology

Welding cycles were imposed to the tube, in a bead on pipe configuration as well as a simulated butt joint with multiples passes, using parameters according to Table 2. The welding was performed on the elbow parts in the 2G welding position, without preheating with Argonium (99.999 % purity level) as protective gas by automated pulsed GTA welding process ARC-05P equipment, and 1.2 mm wire diameter, according to EN ISO 14343-A - G 19 9 Nb Si e AWS A5.9/5.9M ER 347Si standards.

### 2.3. Welding procedure of bead on pipe and simulated butt welding

Elbow I was adopted for the bead on pipe evaluation, using one pass (one bead creating only one welding cycle), and two passes (first bead reheated by the second bead). Several samples were cut from this testpiece and different post welding treatments were applied.

Elbows II and III were adopted for the simulated butt weld. It was only a simulated bevel since no root was welded. A groove was machined in the elbow, as illustrated in Table 3. It was a “V” shaped bevel. The Table 3 also shows a macrographic transversal section of welded joints (2G welding position) in the elbow part II.
2.4. Heat treatment methodology

Fig. 1 describes the PWHT’s thermal cycles (solution heat treatment followed by stabilization) with a temperature-time plot, comprising heating and cooling steps.

2.5. Heat treatment methodologies in weld beads over elbow part I (bead on pipe) and in welded joints of elbow parts II and III

Table 4 describes the identification of the specimens of the weld beads over elbow part I and the conditions that they underwent.

Heat treatments in the weld beads over elbow part I and the “light” ageing were carried out in a muffle furnace, with its own temperature control unit and an independent thermocouple. Solution and stabilization treatments were carried out according to the fabrication standard of the material (ASTM A-403 standard [6]), with cooling in water and still air, until room temperature, respectively. Ageing simulates an extreme condition of temperature around 675°C (within the critical range where the material is supposed to be susceptible to sensitization), according to ASTM A-262 standard [8], although in a “light” mode due to the relatively short time exposure (2h). Cooling was carried out inside the furnace.

Table 5 identifies the specimens of the welded joints in the elbow parts II and III and the conditions that they were subjected.

Samples in this work were subjected to different conditions: stabilization heat treatment and/or “severe” ageing. Stabilization was performed at 850°C for 1h (ASTM A-403 standard [6]), in a "T" type furnace, automated with controlled atmosphere and subsequent cooling of the specimen in still air until room temperature. "Severe" ageing in the specimens of the welded joints of elbow parts II and III was performed in conditions of temperature and time that simulate critical operational periods, that the material can undergo in the serpentines for furnaces as well as pipelines. Ageing was carried out at 600°C for 100h, with the use of a Chromel/Alumel K type thermocouple for temperature control, in a muffle type furnace, where the material was cooled until room temperature.
Table 4 – Identification of the specimens the weld beads over elbow part I.

<table>
<thead>
<tr>
<th>Specimens:</th>
<th>Number of weld passes:</th>
<th>Conditions (following the application order):</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>N/A</td>
<td>As received (without welding)</td>
</tr>
<tr>
<td>A1/1P</td>
<td></td>
<td>As welded</td>
</tr>
<tr>
<td>A2/1P</td>
<td></td>
<td>As welded / Aged (675 °C - 2 h)</td>
</tr>
<tr>
<td>B1/1P</td>
<td></td>
<td>As welded / Solution treated (1040 °C - 1 h - water)</td>
</tr>
<tr>
<td>B2/1P</td>
<td></td>
<td>As welded / Solution treated (1040 °C - 1 h - water) / Aged (675 °C - 2 h)</td>
</tr>
<tr>
<td>C1/1P</td>
<td></td>
<td>As welded / Stabilized (850 °C - 1 h - still air)</td>
</tr>
<tr>
<td>C2/1P</td>
<td></td>
<td>As welded / Stabilized (850 °C - 1 h - still air) / Aged (675 °C - 2 h)</td>
</tr>
<tr>
<td>D1/1P</td>
<td></td>
<td>As welded / Solution treated (1040 °C - 1 h - water) / Stabilized (850 °C - 1 h - still air)</td>
</tr>
<tr>
<td>D2/1P</td>
<td></td>
<td>As welded / Solution treated (1040 °C - 1 h - water) / Stabilized (850 °C - 1 h - still air) / Aged (675 °C - 2 h)</td>
</tr>
<tr>
<td>A1/2P</td>
<td></td>
<td>As welded</td>
</tr>
<tr>
<td>A2/2P</td>
<td></td>
<td>As welded / Aged (675 °C - 2 h)</td>
</tr>
<tr>
<td>B1/2P</td>
<td></td>
<td>As welded / Solution treated (1040 °C - 1 h - water)</td>
</tr>
<tr>
<td>B2/2P</td>
<td></td>
<td>As welded / Solution treated (1040 °C - 1 h - water) / Aged (675 °C - 2 h)</td>
</tr>
<tr>
<td>C1/2P</td>
<td></td>
<td>As welded / Stabilized (850 °C - 1 h - still air)</td>
</tr>
<tr>
<td>C2/2P</td>
<td></td>
<td>As welded / Stabilized (850 °C - 1 h - still air) / Aged (675 °C - 2 h)</td>
</tr>
<tr>
<td>D1/2P</td>
<td></td>
<td>As welded / Solution treated (1040 °C - 1 h - water) / Stabilized (850 °C - 1 h - still air)</td>
</tr>
<tr>
<td>D2/2P</td>
<td></td>
<td>As welded / Solution treated (1040 °C - 1 h - water) / Stabilized (850 °C - 1 h - still air) / Aged (675 °C - 2 h)</td>
</tr>
</tbody>
</table>

Table 5 – Identification of specimens: welded joints of elbow parts II and III.

<table>
<thead>
<tr>
<th>Identification</th>
<th>Elbow part</th>
<th>Conditions (in the application sequence):</th>
</tr>
</thead>
<tbody>
<tr>
<td>E0</td>
<td>II</td>
<td>As received (without welding)</td>
</tr>
<tr>
<td>E1</td>
<td>II</td>
<td>As welded / Stabilized (850 °C - 1 h - still air) / Aged (600 °C - 100 h)</td>
</tr>
<tr>
<td>E2</td>
<td>III</td>
<td>As received (without welding)</td>
</tr>
<tr>
<td>F1</td>
<td>III</td>
<td>As welded / Aged (600 °C - 100 h)</td>
</tr>
<tr>
<td>F2</td>
<td></td>
<td>As welded / Aged (600 °C - 100 h)</td>
</tr>
</tbody>
</table>

2.6. Microstructural characterization methodology

The preparation of metallographic samples comprised; cutting, mounting, grinding (sequence: 100, 220, 320, 400 e 600 mesh) followed by polishing (diamond paste: 15 μm, 6 μm, 3 μm and 1 μm).

2.7. Corrosion tests

These tests evaluate the susceptibility to intergranular corrosion, mainly in the HAZ regions, either on the weld beads under elbow part I or on the welded joints executed on the elbow parts II and III.

2.8. ASTM A-262 — Practice A

The test is executed to verify sensitization though the characterization of the microstructure in “ditch”, “dual” or “step”, that the presence of grains with boundaries revealed by the precipitation of M23C6 carbide particles, a typical “ditch” characteristic, is a strong evidence of sensitization occurrence in this material [8]. Firstly, each specimen was subjected to conventional metallographic preparation and to a solution of 10 % in mass of H2C2O4 2H2O (10.0 g of diluted reagent in 100.0 ml of distilled water) and with the use of a direct current source the polished specimen was attacked by immersion in an acid solution inside a becher with a metallic surface (cathode), with a current density around 1.0 A/cm², at room temperature during 30 s. An optical microscope was used for observation.

2.9. ASTM A-262 — Practice E

This test is carried out, compulsorily, in specimens which were disapproved in the previous test (Practice A of ASTM A-262 standard): occurrence of “ditch” microstructure, but can be executed, optionally, in the presence of “step” or “dual” microstructure types. The specimen used in this test was cold cut and grinded (100–600 mesh) on both sides of the weld [8].

The attack solution was prepared with 6 % in mass of CuSO4 and 16 % in mass of H2SO4 by the dissolution of 100 g of CuSO4·5H2O in 700 ml of deionized water by ionic change and subsequent addition of 100 ml of H2SO4 P. A., further adding 1000 ml with deionized water. Afterwards, at room temperature, the specimens were placed in a 1000 ml capacity Erlenmeyer type flask with glass supporters and their surface coated with 99 % P.A. purity level copper powder for later use in the recipient with 700 ml of the solution and the specimens. The Allihn condenser four bulbs were connected to the flask and to the water supply unit was placed on a heating plate at 300 °C and kept in boiling condition for 15 h. The test onset happens when the solution reaches the boiling point. The attacked specimens were subjected to the 180° bending tests in a universal mechanical tests machine with maximum capacity of 20,000 kgf (196 kN), with compression loads around 2500 kgf (24 kN) with a 11.81 mm diameter punch and the bent specimens were visually checked for cracks detection in the HAZ region, as well as by stereomicroscopy with zoom from 0.67 × to 4.5 × (6.7 × to 90 × magnification) with 6.7:1 zoom ratio.

After bending the specimens were cut to preserve the cracks that were observed. Then the samples were prepared...
3.1. Microstructural of the base metal and the weld beads (beads on pipe)

Table 6 shows the effects of the welding and of the heat treatments on the weld beads over elbow part I, in concern to BM in the different conditions of PWHT or ageing. The “as received” material (A0-BM) presented not only austenite in the microstructure, but also intragranular and intergranular precipitates such as NbC and Cr23C6. NbC are the finest particles in the A0-BM microstructure image, while intergranular attack is associated to Cr23C6 precipitates. Table 7 shows the effects of the heat treatments on the weld beads over elbow part I, in concern to interfaces between HAZ, Fusion Line (FL) and Weld Metal (WM), in the different conditions of PWHT or ageing. However, the WM region was not focused in this work.

3. Results and discussion

3.1. Microstructural of the base metal and the weld beads (beads on pipe)

Table 6 shows the effects of the welding and of the heat treatments on the weld beads over elbow part I, in concern to BM in the different conditions of PWHT or ageing. The “as received” material (A0-BM) presented not only austenite in the microstructure, but also intragranular and intergranular precipitates such as NbC and Cr23C6. NbC are the finest particles in the A0-BM microstructure image, while intergranular attack is associated to Cr23C6 precipitates.

Among evidences of microstructural transformations (Tables 6 and 7) only the effects of welding and cooling did not lead to the complete dissolution of NbC precipitates, either in the BM region (A1-BM) or in the A1/1P-HAZ/FL/WM interfaces, considering one or two weld beads over the piece. Thus, the presence of primary, coarse and incoherent NbC precipitates, as well as fine secondary precipitates inside the grains and also on grain boundaries and non dissolved coarser Nb(C,N) particles was observed. The thermal effects of welding without subsequent ageing did not cause sensitization, although some intergranular M23C6 without surrounding completely these grains occur, thus preserving the effect of the original stabilization of the material, mainly in the HAZ region.

On the other hand, following ageing after welding (Tables 6 and 7), the microstructure reveals sensitization in the A2/1P-HAZ/FL/WM interfaces, characterized by precipitated carbide particles on grain boundaries of austenitic grains, thus showing intergranular corrosion. In concern to the BM (A2-BM), the original stabilization of the “as received” condition avoided sensitization, but probably due to the morphology, some M23C6 precipitates were still observed on the austenitic grain boundaries, as well as coarser non dissolved Nb(C,N) precipitate particles.

In the weld beads over the elbow part (bead on pipe) which underwent some kind of PWHT, such as solution and/or stabilization, with or without ageing after these heat treatments (Table 7), the PWHT’s avoided sensitization on the HAZ, with sluggish precipitation of M23C6 on the grain boundaries (B2/1P-HAZ/FL/WM, C2/1P-HAZ/FL/WM and D2/1P-HAZ/FL/WM), as well as twinning caused by low stacking fault energy and some primary (coarse) NbC particles with higher thermodynamic stability, which were not dissolved during the heat treatments.

Table 7 for C2/1P-HAZ/FL/WM revealed, probably queued precipitates of M23C6, not necessarily on the grain boundaries, but on narrow region, parallel to the weld bead, between the HAZ and the BM, more distant to the FL. Perhaps these precipitates can contribute to incisive corrosion, due to the fact that after solution PWHT part of the NbC carbides were dissolved and upon rapid cooling, although not so fast, in the 600–850 °C range it is possible that some initial precipitation of Cr has occurred, since it is more favorable from a kinetical viewpoint, considering that the Cr atoms diffusion becomes quicker than the one of Nb atoms and Cr is present with a higher concentration [1].

In some weld beads, after welding with one or two passes, PWHT’s of solution were followed by stabilization, without and with (Table 7 for D2/1P-HAZ/FL/WM) subsequent ageing. After long exposure time, the probable M23C6 carbides were replaced by MC ones, which are more stable. The precipitation of secondary MC carbides occurred preferentially on the grain boundaries [1]. D2/1P-HAZ/FL/WM shows a series of small carbide particles, mainly M23C6 on the grain boundaries but without surrounding completely these grains, and NbC both on the grain boundaries and inside the grains. Comparison with samples which underwent PWHT’s, or even only solution treatment, or only stabilization, shows that samples subjected to complete solution treatment followed by stabilization provided a higher amount of M23C6 precipitates.

In concern to the BM of these showed weld beads (Table 6 for B2-BM, C2-BM and D2-BM cases), the application of PWHT’s
did not provide the complete dissolution of $\text{M}_{23}\text{C}_6$ precipitates, with or without ageing, mainly in the samples that underwent only stabilization as heat treatment (C2-BM). However, in all situations, the $\text{M}_{23}\text{C}_6$ precipitates did not surround completely any grain, not revealing sensitization in case of ageing. On the other hand, coarse NbC precipitates were observed inside the grains in D2-BM samples.

It should be emphasized that the implementation of any of the following combinations of PWHT’s: i) dissolution of carbides above 1000 °C followed by fast cooling in water; ii)

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**Table 6 - Microstructure images of transversal sections of the BM for the elbow part I in different heat conditions. Electrolytic etching with oxalic acid solution.**

<table>
<thead>
<tr>
<th>Sample-Location</th>
<th>Microstructure Image</th>
<th>Heat treatment condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0-BM</td>
<td><img src="Image1" alt="Image" /></td>
<td>&quot;As received&quot; BM, without the welding effects and without additional heat treatment.</td>
</tr>
<tr>
<td>A1-BM</td>
<td><img src="Image2" alt="Image" /></td>
<td>BM with the welding effects and without ageing.</td>
</tr>
<tr>
<td>A2-BM</td>
<td><img src="Image3" alt="Image" /></td>
<td>BM with the welding effects followed by ageing (675 °C - 2 h).</td>
</tr>
<tr>
<td>B2-BM</td>
<td><img src="Image4" alt="Image" /></td>
<td>BM with the welding effects followed by solution annealing PWHT (1040 °C - 1 h - water) and then ageing (675 °C - 2 h).</td>
</tr>
<tr>
<td>C2-BM</td>
<td><img src="Image5" alt="Image" /></td>
<td>BM with the welding effects followed by stabilization (850 °C - 1 h - still air) and then ageing (675 °C - 2 h).</td>
</tr>
</tbody>
</table>
stabilization at 850 °C followed by slow cooling until room temperature; c) solution heat treatment followed by stabilization, in the previously described conditions; in all cases with subsequent ageing at 675 °C, did not cause sensitization on the HAZ and BM regions, with one or two passes in the weld beads, consequently achieving intergranular corrosion resistance.

### 3.2. Corrosion resistance

3.2.1. ASTM A-262 — Practices A and E

Table 8, 9, and 10 indicate the results of qualitative corrosion tests according to Practices A and E of ASTM A-262 standard [8].

Table 8 presented the micrographs obtained with the metallocraphic etchant prescribed by Practice A of ASTM A-262 standard [8], in the interfaces between HAZ/FL/WM of the welded joint of elbow part III in the conditions: aged and PWHT of stabilization followed by ageing, respectively. In F2-HAZ/FL/WM interfaces precipitates of the metastable phase M_{23}C_6 are observed. The precipitation of these carbides was kinetically favored and they surrounded completely almost all austenitic grains (“ditch” aspect), thus testifying the intense sensitization that happened in the HAZ. On the other hand, in F1-HAZ/FL/WM interfaces M_{23}C_6 precipitates can also be seen on grain boundaries, but with a “dual” aspect, as well as coarse Nb(C,N) particles, finer NbC particles and coarser NbC particles inside the grains through morphological observation. MC type carbides, more stable than the M_{23}C_6 type carbides, appeared in the stabilized samples, with the dissolution of these ones, mainly after long ageing time.

Among the mechanical tests performed in the aged welded joints (Practice E of ASTM A-262 standard [8]) there was a bending test in the region of interest (HAZ/FL/WM interface) with the purpose of observing the occurrence of cracks as consequence of intergranular corrosion, thus achieving the macrographic and micrographic images presented in the Tables 9 and 10, respectively. These samples were subjected only to the ageing and PWHT of stabilization followed by ageing, respectively.

Table 9 presented the macrographic images of the HAZ of the welded joints after the bending operation. In F1-HAZ/FL/WM after the bending operation cracks were not observed, only in welded joint subjected to ageing and then to bending (F2-HAZ/FL/WM interface) cracks were seen as consequence of intergranular corrosion in the HAZ.

In Table 10 for F2-HAZ/FL/WM after the bending test it is noted on the grain boundaries regions (with higher energy) the presence of M_{23}C_6 precipitates, revealing intergranular corrosion, as practical effect of mechanical bending, fracture in the HAZ of the welded joints near the FL and parallel to the WM with 200 μm long cracks. On the other hand, F1-HAZ/FL/WM after the bending test presented only a few microcracks on the grain boundaries, which, on the contrary of the cases without stabilization PWHT, cannot be observed with the naked eye or by optical microscopy. ASTM A-262 standard [8] determines that the bent specimens must be necessarily examined with low magnification (between 5 × and 20 ×) and even in 50 × magnification these microcracks already appear and have less significant brittle effects.

### 3.3. DL-EPR

In order to evaluate the susceptibility to sensitization in different regions of the welded joints of elbow parts II and III (mainly BM and HAZ), the technique of DL-EPR was used, with plots of current density (A/cm²) vs. potential (V SCE) in Fig. 2 and the DOS in each one of the regions of the welded joints, in Table 11, as well as in Tables 12 and 13, with micrographic views on the DL-EPR test regions of the welded joints of elbow part II: i) “as received” (BM region), only aged BM, and BM with PWHT of stabilization followed by ageing; and ii) for WM/FL/HAZ interfaces, “As welded” followed by ageing and “As welded” followed by stabilization and then ageing, respectively.

Through observation of the plots shown in Fig. 2, only in the HAZ regions (Table 13) sensitization occurred by increasing the values in the reactivation curves, independently on the performing PWHT sensitization before ageing. However, with the application of a stabilization treatment, the increase levels were smoother, with DOS of 3.13 % for E1 and 2.95 % for F1 (Table 11), which can be considered acceptable for not surpassing the limit value of 5 %. On the other hand, without any type of PWHT unless ageing, the values were 6.57 % for E2 and 15.80 % for F2, as can be seen by the grains completely surrounded by M_{23}C_6 on the HAZ region of the welded joints subjected only to ageing, like showed in the Table 13 for E2-HAZ/FL/WM interface.

Low welding energy can limit, but not completely suppress sensitization in the HAZ region of the welded joint of austenitic stainless steel without PWHT. The reason for the DOS of F2 being much higher than the one of E2 is due prob-
Table 7 - Microstructure images of transversal sections of the HAZ/FL/WM interfaces for the weld beads over elbow part I specimen in different heat conditions. Electrolytic etching with oxalic acid solution.

<table>
<thead>
<tr>
<th>Sample-Location</th>
<th>Microstructure Image</th>
<th>Heat treatment condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1/1P-HAZ/FL/WM</td>
<td>&quot;As welded&quot;.</td>
<td></td>
</tr>
<tr>
<td>A2/1P-HAZ/FL/WM</td>
<td>&quot;As welded&quot; followed by ageing (675 °C - 2 h).</td>
<td></td>
</tr>
<tr>
<td>B2/1P-HAZ/FL/WM</td>
<td>&quot;As welded&quot; followed by solution annealing PWHT (1040 °C - 1 h - water) and then ageing (675 °C - 2 h).</td>
<td></td>
</tr>
<tr>
<td>C2/1P-HAZ/FL/WM</td>
<td>&quot;As welded&quot; followed by stabilization (850 °C - 1 h - still air) and then ageing (675 °C - 2 h).</td>
<td></td>
</tr>
<tr>
<td>D2/1P-HAZ/FL/WM</td>
<td>&quot;As welded&quot; followed by solution annealing PWHT (1040 °C - 1 h - water), stabilization (850 °C - 1 h - still air) and then ageing (675 °C - 2 h).</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 showed that sensitization in the BM regions of the welded joint was not significant with DOS lower than 0.76 % (Table 11) since the influence of the thermal cycle of welding on microstructure changes was minimal. Therefore, grains completely surrounded by $M_{23}C_6$ precipitates were not observed, but only in some regions of the boundaries, as well as fine carbide precipitates of NbC and particles of Nb(C,N) inside the grains, in E0-BM, E1-BM and E2-BM specimens.
Table 8 – Microstructure images of transversal sections of the BM and of the HAZ/FL/WM interfaces for the welded joint of the elbow part III specimen in different heat conditions. Corrosion test by Practice A of ASTM A-262 standard [8]. Electrolytic etching with oxalic acid solution.

<table>
<thead>
<tr>
<th>Sample-Location</th>
<th>Microstructure Image</th>
<th>Heat treatment condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1-HAZ/FL/WM</td>
<td><img src="image1" alt="Image" /></td>
<td>“As welded” followed by stabilization (850 °C - 1 h - still air) and then ageing (600 °C - 100 h).</td>
</tr>
<tr>
<td>F2-HAZ/FL/WM</td>
<td><img src="image2" alt="Image" /></td>
<td>“As welded” followed by ageing (600 °C - 100 h).</td>
</tr>
</tbody>
</table>

Table 9 – Macrostructure images of transversal sections of the HAZ/FL/WM interfaces for the welded joint of the elbow part III specimen in different heat treatment conditions.

<table>
<thead>
<tr>
<th>Sample-Location</th>
<th>Macrostructure Image</th>
<th>Heat treatment condition / Test information</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1-HAZ/FL/WM</td>
<td><img src="image3" alt="Image" /></td>
<td>“As welded” followed by stabilization (850 °C - 1 h - still air) and then ageing (600 °C - 100 h). Bent after the bending test - Practice E of ASTM A-262 standard [8].</td>
</tr>
<tr>
<td>F2-HAZ/FL/WM</td>
<td><img src="image4" alt="Image" /></td>
<td>“As welded” followed by ageing (600 °C - 100 h). Bent after the bending test - Practice E of ASTM A-262 standard [8].</td>
</tr>
</tbody>
</table>
Table 10 – Microstructure images of transversal sections of the HAZ/FL/WM interfaces for the welded joint of the elbow part III bent specimen after the bending test by Practice E of ASTM A-262 standard [8], in different heat treatment conditions. Electrolytic etching with oxalic acid solution.

Sample-Location: Microstructure Image: Heat treatment condition:

F1-HAZ/FL/WM

*As welded* followed by stabilization (850 °C - 1 h - still air) and then ageing (600 °C - 100 h).

F2-HAZ/FL/WM

*As welded* followed by ageing (600 °C - 100 h).

Table 11 – DOS for each condition of the specimens in each region (BM or HAZ) in the welded joints of elbow parts II and III.

| Identification | Condition: | Welded Joint Region: | ASTM A-262 – Practice A | ASTM A-262 – Practice E | DOS (%) | Situation:
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>E0</td>
<td>As Received (without Welding)</td>
<td>BM</td>
<td>“Dual”</td>
<td>Not Evaluated</td>
<td>0.32 %</td>
<td>Non-sensitized</td>
</tr>
<tr>
<td>E1</td>
<td>As</td>
<td>BM</td>
<td>“Dual”</td>
<td>Not Evaluated</td>
<td>0.27 %</td>
<td>Non-sensitized</td>
</tr>
<tr>
<td>F1</td>
<td>Welded + Stabilizing</td>
<td>HAZ</td>
<td>Few micro cracks</td>
<td>3.13 %</td>
<td>Non-sensitized</td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>Anneal + Thermal</td>
<td>BM</td>
<td>Few micro cracks</td>
<td>2.95 %</td>
<td>Non-sensitized</td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>Aging</td>
<td>BM</td>
<td>“Dual”</td>
<td>Not Evaluated</td>
<td>0.42 %</td>
<td>Non-sensitized</td>
</tr>
<tr>
<td>F2</td>
<td>As Welded + Thermal</td>
<td>BM</td>
<td>“Ditch”</td>
<td>Lots of macro cracks</td>
<td>6.57 %</td>
<td>Sensitized</td>
</tr>
<tr>
<td>E2</td>
<td>Aging</td>
<td>HAZ</td>
<td>“Ditch”</td>
<td></td>
<td>15.80 %</td>
<td>Sensitized</td>
</tr>
</tbody>
</table>

DOS ≥ 5 % - "Sensitized"; DOS < 5 % - "Non-sensitized".

Table 12 – Microstructure images of transversal sections of the BM for the elbow part II specimen on the DL-EPR test regions in different heat treatment conditions. Etching by the electrolyte solution during the DL-EPR test.

Sample-Location: Microstructure Images: Heat treatment condition:

E0-BM

*As received* BM, without the welding effects and without additional heat treatment.
Table 12 (Continued)

<table>
<thead>
<tr>
<th>Sample-Location</th>
<th>Microstructure Images</th>
<th>Heat treatment condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1-BM</td>
<td>![Image of BM with welding effects], 200 μm</td>
<td>BM with the welding effects followed by stabilization (850 °C - 1 h - still air) and then ageing (600 °C - 100 h).</td>
</tr>
<tr>
<td>E2-BM</td>
<td>![Image of BM with welding effects], 200 μm</td>
<td>BM with the welding effects followed by ageing (600 °C - 100 h).</td>
</tr>
</tbody>
</table>

Fig. 2 - Plots: Current Density (A/cm²) vs. Potential (V SCE) in different regions of the welded joints of elbow parts II and III through DL-EPR.
3.4. Considerations about PWHT

The application of the solution PWHT with the purpose of dissolving carbides, mainly the discontinuous ones, and the films of carbides present on the grain boundaries. The subsequent ageing treatment allow a better control of the following precipitation of secondary carbides, also enabling a more intense precipitation of these carbides that results in higher resistance to creep. When the material is subjected to a higher solution temperature, there is a significant improvement of the distribution of secondary carbides precipitates inside the grains, due to a more uniform distribution of the elements that are components of these phases [1].

The drawback of stabilization PWHT relies on the fact that temperatures higher than 1000 °C are necessary, thus hindering field activities, as well as the possibility of the generation of thermal stresses in the HAZ of welded joints of large diameter or thickness pieces. Therefore, even with the necessity of PWHT in HAZ regions of Nb stabilized austenitic stainless steel, in order to avoid sensitization, one of the most viable options, and technically similar to solution treatment, from the operational viewpoint, is the application of stabilization PWHT alone.

Thus, in the welded joints two basic conditions were analyzed: i) stabilization followed by ageing at 600 °C for 100 h; ii) only ageing in the same temperature and time in two identical samples: welded joints E and F.

Different from HAZ, in the BM the accomplishment of PWHT’s is indifferent, since the original treatment performed by the supplier in these Nb stabilized materials is sufficient to avoid sensitization. On the other hand, in the HAZ, due to the high heat inputs provided by welding and with ageing in the critical range for sensitization, there is a strong tendency for destabilize this region, thus requiring a new stabilization procedure, before subjecting the welded joints to ageing in service.

4. Conclusion

- Welds of AISI 347 SS without PWHT are susceptible to sensitization in services at high temperature.
- Solution treatment of the whole welded piece followed by local stabilization, or only the application of local stabilization, were efficient means for prevention of intergranular corrosion.
- Stabilization PWHT of previously stabilized steel was not necessary in the whole welded joint, since in the base metal (BM) stabilization was clearly sufficient to prevent sensitization.
- In service conditions when a welded component of AISI 347 SS is exposed to around 450 °C, PWHT’s are optional, since even in the welded joint the original NbC is sufficient to prevent sensitization phenomenon in the welded joint.
- In service conditions when temperature is above 450 °C, but in a uniform 600 °C level, for instance, it is mandatory the application of local stabilization heat treatment in the HAZ. However, large temperature variations in the piece in service, between 550 °C and 700 °C, for instance, make necessary the solution heat treatment in the whole piece, followed by local stabilization in the HAZ.
Conflicts of interest

The authors declare no conflicts of interest.

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