Original Article

Mechanical properties and microstructure of SMAW welded and thermally treated HSLA-80 steel

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\textbf{A R T I C L E   I N F O}

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\textbf{A B S T R A C T}

This paper aims to present a comparison on the use of different heat treatment conditions in association with welding of a HSLA-80 steel. This investigation was carried out by multipass welding using the coated electrode process in different heat treatment conditions, with or without pre- or post-weld heating, in order to compare effects on the mechanical properties and microstructure for each condition. After welding was performed, procedures to identify microstructural phases and characterize the mechanical behavior were carried out. The results of mechanical tests and metallographic analysis were conclusive that heat treatments are not necessary to complement welding procedures of this steel. This is especially the case of the post-welding heat treatment. In fact, the application of these treatments did not significantly affect neither the microstructure nor the mechanical characteristics of the material.

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1. Introduction

Methods that aim at the optimization of welded steel structures, such as improvement of properties and reduction of failures, have been extensively investigated by research groups around the world [1–7]. Welding is an important stage in the manufacture of metallic structures used in many sectors such as oil and shipbuilding. Welding technologies involved in the manufacture of these structures assume fundamental relevance. For instance, in the oil and gas sector, submerged components (pipelines, rigs and vessels) usually present welding defects and discontinuities that are responsible for the nucleation and propagation of cracks that might impair their integrity [8,9].

Several types of steels can be used for the manufacture of parts applied in these sectors and have desired technological properties when welded. Among them, high strength low alloy steels (HSLA) are not only mostly applied but also recommended by standards [8]. HSLA steels are developed to promote better mechanical properties, especially superior toughness as well as higher resistance to atmospheric corrosion than conventional carbon steels. Such steels are generally manufactured by controlled rolling followed by accelerated cooling or by a normalizing heat treatment. Among these steels, the HSLA-80 was specifically developed for use in pipelines and ship hull, some of them to operate in extremely cold regions. One of the main characteristic of this steel is the precipitation hardenable of Cu, which occurs from the supersaturated ferrite, between 480 and 705 °C [10].

Recent works have reported on properties and/or welding conditions of HSLA-80 steel. Thompson [11] compared this steel with HSLA-80/100 and HSLA-100, based on plots involving yield strength, Charpy test absorbed energy and shear fracture appearance. The author found that the plots are acceptable for predicting the influence of microstructure on the combination of strength and toughness. Durmusoglu et al. [12] indicated that HSLA-80 steel joined by gas metal arc weld presents the strength of both weld metal and heat affected zone (HAZ) higher than that of the base metal. As for the microstructure, the authors indicated that martensite needles and bainite are seen in the HAZ, while the weld metal has also residual austenite. Yang et al. [13] investigated welding shrinkage and distortion in thinner welded structures of HSLA-80 and other steels, such as ABS Grade DH-36 lower strength hull steel. For the same welding heat input, as thickness increases, shrinkage and distortions are reduced for both higher and lower strength steels. Castro et al. [14] correlated boundary misorientations with acicular microstructure by electron microscopy and electron backscatter diffraction, EBDS. They found that thermomechanical treatments with continuous cooling were more effective than isothermal ones to obtain that microstructure. Shat et al. [15] observed precipitates of different morphologies and size ranges in HSLA-80 pipeline steel with reduced Mn content. They concluded that this specific steel is suitable for sour service application. Cruz-Crespo et al. [16] analyzed the HAZ microstructure and hardness of API SL X 80 microalloyed steel subjected to welding thermal cycles. Their results indicate that this steel has high weldability without the need of pre-heating to prevent cold cracking.

HSLA-80 steel presents low susceptibility to cracking by hydrogen [15], therefore, it exhibit a good weldability. In principle, it should not necessarily be subjected to thermal treatments pre- or post-welding [4]. Although some researchers do not recommend heat treatment prior to the welding process of this steel [17], there are studies that suggest that these treatments can improve the properties of the final welded joint. According to Keeha [18], heating and cooling conditions can promote a sensible influence in the microstructure of the weld bead. The practical importance of HSLA-80 steel, mainly for the oil and gas industrial sector, justify a deeper investigation on heat treatment effects. In particular, this steel is extensively used in petroleum pipelines that must be welded with strict requirements of strength and toughness [15]. Heat treatment of the weld bead is still a question open to discussion. Thus, this work aims to evaluate the influence on the mechanical and microstructural properties of HSLA-80 steel joints welded by the shield metal arc welding (SMAW) process under different heat treatment conditions.

2. Materials and methods

The high strength low alloy (HSLA) ASME type 80 investigated steel was supplied as plates by Arcelor Mittal, France, with the composition presented in Table 1. The welding electrodes were purchased from Air Liquid Welding, France with the composition shown in Table 1. Basic mechanical properties of the steel, associated with the base material in this work, are also shown in Table 1.

For this study, HSLA-80 steel plates were used in the dimensions of 3000 mm × 250 mm × 30 mm. Three sets of specimens were made in the dimensions of 500 mm × 250 mm × 30 mm, one for each different heat treatment route. Table 2 exhibit the heat treatment conditions applied to the HSLA-80 steel. As indicated in this table, CPR means pre-heating treatment (70/110 °C for 2 h); CPO means post-heating treatment (170 °C for 5 h); SPR means without pre-heating; and SPO means without post-heating. The whole experiment focused on the regions of weld metal (WM) or fusion zone (FZ) and heat affected zone (HAZ), seeking mechanical and microstructural analyses.

The assemblies to be welded were prepared with double “V” bevel profile, angle of 60°, ratio of 1/3 (10 mm) and 2/3 (20 mm) in the formation of the bevel, root opening of 5 mm ± 1 mm tolerance. The welding was carried out by the coated electrode SMAW process, in flat position (1G), with AWS/ASME E 11018-G basic type electrode addition material with high mechanical strength and high toughness at low temperatures (760–820 MPa). Fig. 1(a) shows the geometry of the joint used and Fig. 1(b) presents the preparation of the material with a first pass in the root and with plates of entry and exit of weld. Welding was performed with the cord following the rolling direction.

The welding parameters used in the root, filling and top stages as well as the heat input and electrode diameter are presented in Table 3.

Fig. 2 presents the pre- and post-weld heat treatment program used in the present investigation. As shown in these programs, the pre-heating before welding was performed with
Table 1 – Chemical composition (wt%) and mechanical properties of HSLA-80 steel as well as chemical composition (wt%) of AWS A-5.5 E11018G electrodes.

<table>
<thead>
<tr>
<th>Composition of the HSLA-80 steel</th>
<th>Composition of the AWS A-5.5 E11018G electrodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Mn</td>
</tr>
<tr>
<td>0.07</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Mechanical properties of the HSLA-80 steel

<table>
<thead>
<tr>
<th>Yield stress (MPa)</th>
<th>Ultimate strength (MPa)</th>
<th>Elastic modulus (GPa)</th>
<th>Total strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>450 ± 32</td>
<td>778 ± 17</td>
<td>203 ± 5</td>
<td>21 ± 2</td>
</tr>
</tbody>
</table>

controlled temperature between 70 and 110 °C, as indicated by the dashed line (1) in Fig. 2, for about 2 h. During welding procedure, the materials was kept at a minimum temperature of 70 °C, dotted line (2), with a maximum at 125 °C between each pass. The post-heating treatment was conducted at just the end of the welding procedure, not allowing the welded joint to cool below 70 °C, by raising and maintaining the temperature at 170 °C, solid line (3), for about 5 h. After this time, the heater (electrical resistances surrounding the weldment) was turned off.

For macrographic analysis, the surface of the samples was polished and chemically attacked with Nital. The observation was performed with naked eye. The macrograph images were obtained with the aid of a Nikon Coolpix model P6000 camera.

Micrographic analysis was done with the aid of a TECHNICAL optical microscope model CGA. Samples were prepared by conventional polishing and attack with Nital. The region evaluated was the cross section of the welded joint in its root, filling facing and finishing stages. Scanning electron microscopy (SEM) observations were performed in a model QUANTA FEG 250 Fei microscope operating with secondary electrons.

For the determination of the Vickers microhardness, a WPM-type durometer, model HPO 250, was used. A load of 1 kgf was applied using 18 measurements in the base metal (BM), 8 measurements in the heat affected zone (HAZ), and 8 in the weld metal fusion zone (FZ). Fig. 3 illustrates the selected points for these measurements.

The tensile tests followed the ASTM A370 standard [19] and were performed on rectangular and cylindrical specimens for cross-weld and weld bead evaluations respectively. A total of 5 ASTM standard specimens was tensile tested for each condition. Charpy V-notched specimens were machined according to the standard [19] and initially immersed in ethyl alcohol at −20 °C in an isothermal vessel. The impact tests were performed in a model JBW-300 Panantec Atmi pendulum impact machine. These tests were performed under the following conditions: impact velocity of 5.2 m/s, 22 °C room temperature (~25 °C), and 54% of relative humidity. The Charpy specimens had the notch machined either in the HAZ or in the WM. A total of 5 specimens was impact tested for each condition. Fig. 4 illustrates schematically the shape of both flat and round ASTM standard tensile specimens as well as the shape of standard Charpy-V specimens with indication of their position in the welded joint. In this figure, it is also schematically shown the positions where metallographic samples were obtained.

3. Results and discussion

Fig. 5 shows the cross-sectional macrograph of the central region of the welded joint. It was noted that all welding
procedures occurred satisfactorily. The deposition were performed without any type of defect and the casting was characterized by the double “V” bevel, thus revealing all the layers of welding and the corresponding passes that compose them. It was also observed an excellent definition of the region of the heat affected zone (HAZ) (darker region) and also the base metal (BM) (lighter region).

Fig. 6 displays a SEM image of different microstructures of the welded joint, extended from the weld metal (WM) through the HAZ, in its initial condition without post-heat treatment. In this figure, a clear distinction exists between the WM and HAZ, which depicts a fine bainite (FB) microstructure. The WM microstructure is predominantly composed of acicular ferrite (AF) with strings of grain boundary ferrite (GF).

The microstructure developed around the welded joint, Fig. 6, have also been reported in the literature. For the WM it is observed, that the microstructure in this region is basically AF [12]. The same result was obtained by Farrar and Harrison [20]. Karlsson et al. [21] state that high strength WM microstructures are due to AF, bainite and martensite in steels with the content on Ni in between of 2 and 3%. The presence of AF in the WM is highly desirable, since it represents a gain in the mechanical properties of the weld bead, ensuring high tenacity of the welded joint [17,20,22].

Fig. 7 shows the micrographs obtained by optical microscopy of BM. A typical bainite microstructure is characteristic of the BM, which agrees with the technical information provided by the supplier.

With post-heat treatment, a high welding energy due to the heat input, promotes the formation of GF and also intragranular ferrite (IF), when associated with the pre-heat weld treatment (CPR). The increase in temperature before welding resulted in the reduction in the cooling rate of the WM (sample CPR/CPO). The slower cooling rates may have induced the nucleation of IF or generating GF. Fig. 8 details the welded joint for each of the four heat treatments used. For all the samples heat-treated in the different conditions tested in the present work, there was the presence of bainite in the HAZ and of AF in the WM as columnar grains in the regions of the fusion zone.
reinforcing the statements of Hashiba et al. [23] and of Farrar and Harrison [20].

Another preliminary result obtained from the microstructural analysis performed on the HSLA-80 steel weld joint, Fig. 8, was the presence of about 40% of columnar and 60% of reheat regions. The columnar microstructure is basically formed by AF and its occurrence in the WM might be associated with elements such as Mn and Ni that exist in the electrodes, Table 1. These elements are AF stabilizers. The columnar AF displays a fine and intertwined lamellae. The random distribution of these lamellae probably favors a higher toughness of the WM. Not only AF but also bainite contributes to improve both the toughness and strength of the welded joint. It is suggested that the presence of this columnar microstructure and not the pre-heating treatment, is the responsible for the welded joint performance.

Microhardness measurements reveal only small differences due to the effect of heat treatment on the welded joint. The SPR/SPO condition, without pre-or post-heating (Table 2) exhibited the highest WM hardness average of 332 HV. A superior hardness level obtained by this condition is probably associated with the absence of preheating, which results in a higher cooling rate. Effective formation of AF is thus induced in comparison with conditions related to pre- and post-heating treatment. These results are comparable to those obtained by Yayla et al. [24]. Fig. 9 presents the plots for microhardness values measured across the BM-HAZ-WM-HAZ-BM for the four conditions.
different conditions indicated in Table 2. As seen in this figure, the WMs display greater microhardness values followed by those in HAZs. It is also important to notice in Fig. 9 that the microhardness profile and associated values do not differ significantly for the investigated heat treatments.

In all tensile tests, the specimens had a behavior within the desirable, with the fracture occurring in the BM. In addition, the values of the yield and rupture strengths, 415 and 502 MPa, respectively, were within the expected ones for this material. Table 4 shows the results obtained by tensile tests for both flat (transversal) and cylindrical (longitudinal) specimens in relation to the weld cord.

All the broken tensile specimens exhibited the cup and cone aspect that characterizes the welded joint as ductile. This behavior is desirable in this type of steel, since it indicates that although the welding cause changes in the final microstructure of the weld metal, these did not influence significantly the mechanical properties of the material.

With respect to the Charpy impact test, the results showed that the interaction of welding and post-heating treatment (CPO) were able to promote an increase in absorbed energy in the HAZ region, and the inverse effect for the WM. This behavior is shown in Fig. 10. Charpy specimens with the notch in the HAZ display comparatively higher toughness than those with the notch in the WM, except for the no-heat-treatment condition, SPR/SPO (Table 2). This heat treatment effect on the absorbed energy could be a consequence of the heterogeneous microstructure developed in the welded joint.

It was also observed that the impact strength in the WM is directly influenced by the presence of AF and the sample that had the tendency to exclusively form this microstructure was condition SPR/SPO. Therefore, it is believed that this microstructure was formed due to the higher cooling rate. The results obtained in mechanical tests, Figs. 9, 10 and Table 4, as well as microstructure analysis showed that the heat treatments did not significantly affect the mechanical properties and the microstructure of the HSLA-80 steel. This may indicate that condition CPR/CPO, usually applied in the sectors of shipbuilding and oil industry, can be discarded and replaced by condition SPR/SPO. Indeed, it should be noted that the two conditions presented comparable results in all test analyses, and are within the requirements established by the ASME IX standard [9].

4. Summary and conclusions

- Coated electrode welding of HSLA-80 steel was subjected to different conditions: just pre-heating; pre- and post-heating; just post-heating; and without pre- or post-heating. The results revealed only minor influence of any heat treatment usually applied in association with welding of this steel.

- Specimens that did not have welding pre-heating showed basically columnar acicular ferrite in the weld metal microstructure, due to a higher cooling rate. This promoted slightly better tenacity as well as relatively higher hardness.

- The condition of pre- and post-heating, in addition to 40% of acicular ferrite, induced the formation of grain boundary ferrite and small amount of intergranular ferrite. Around 60% of reheated regions were formed and might have impaired the performance of the welded joint.

- Microhardness measurements disclosed significantly higher values in the weld metal, particularly for condition corresponding to the absence of either pre- or post-heating.

- The toughness measured by Charpy impact absorbed energy was higher in the HAZ than in the weld metal for the heat-treated conditions. However, the toughness of the weld metal was higher for the non-pre- or post-heat treated condition.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Yield strength (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Total strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat transversal</td>
<td>415 ± 5</td>
<td>502 ± 3</td>
<td>17 ± 2</td>
</tr>
<tr>
<td>Cylindrical longitudinal WM – SPR/CPO</td>
<td>825 ± 3</td>
<td>884 ± 4</td>
<td>19 ± 2</td>
</tr>
<tr>
<td>Cylindrical longitudinal WM – CPR/SPO</td>
<td>856 ± 9</td>
<td>913 ± 11</td>
<td>21 ± 1</td>
</tr>
<tr>
<td>Cylindrical longitudinal WM – SPR/CPO</td>
<td>854 ± 5</td>
<td>903 ± 8</td>
<td>27 ± 1</td>
</tr>
<tr>
<td>Cylindrical longitudinal WM – SPR/SPO</td>
<td>862 ± 6</td>
<td>918 ± 7</td>
<td>24 ± 3</td>
</tr>
</tbody>
</table>
Tensile strength values also indicated only slightly higher values for the weld metal in the condition without pre- or post-heating.

Based on these results, it is concluded that heat treatments usually recommended for HSLA-80 steel, in practice should significantly affect neither the mechanical behavior nor the microstructure of welded joints.

**Conflicts of interest**

The authors declare no conflicts of interest.

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