Effect of V on the Strengthening and Fatigue Behavior of a High-Strength Low-Alloy Steel Welded Joint

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ABSTRACT

The development of high-strength steel (HSLA) for structural applications, including wind towers, offshore structures and shipbuilding, requires a continuous effort to achieve the balance between high strength, toughness and weldability. During a multiple-pass welding, the intercritically reheated grain coarsened heat-affected zone (IC GC HAZ) represents the most brittle section of HSLA steels welds. The presence of microalloying elements in HSLA steels induces the formation of microstructural constituents, capable of improving the mechanical performance of welded joints, such as fatigue resistance and toughness. The scope of this study is to investigate the influence of vanadium addition on the behaviour of IC GC HAZ in S355 steel grade. Different welded samples were carried out by robotic Gas Metal Arc Welding (GMAW) process, involving multiple passes on high-thickness S355 steel plates, varying the addition of vanadium as a microalloying element. The results of the microstructural analysis reveal diverse microstructures, including bainite, martensite and pearlite-ferrite, present in both the heat-affected zone (HAZ) and the weld zone (WZ). Additionally, a discernible change in grain size is observed in the intercritical HAZ. Regarding the microhardness evaluation, it is evident that the presence of vanadium influences the behavior of this property, even showing minimal variation in the vanadium-enhanced weld root.

Keywords: HSLA steel, GMAW Robotic process, vanadium micro-alloying, microhardness evaluation

INTRODUCTION

The constant demand in the energy sector for materials with outstanding mechanical properties, such as toughness and strength, coupled with good weldability and the need to reduce manufacturing costs, has driven the development of high-strength low-alloy steels (HSLA) (1,2). These steels incorporate microalloying elements such as niobium, vanadium, or titanium, allowing them to enhance their strength-to-weight ratio, making them ideal for applications in pipelines, storage tanks, pressure vessels, among others, typically manufactured in thick gauges (3–6). Among the mentioned elements, vanadium stands out as a highly interesting element in the metallurgical design of modern HSLA steels, owing to its thermodynamic and kinetic properties for forming precipitates in the form of nitrides and carbides (7–9).

The manufacturing of components in HSLA steel requires the use of welding processes, which demands a detailed study and analysis of the changes the material undergoes during the process. In fact, the inherent thermal gradients in joining technologies significantly influence the mechanical behavior and microstructural development of the joint. The selection of the welding process, as well as its operating parameters, are essential factors for achieving high-quality joints and outstanding mechanical performance (10–12). The Gas Metal Arc Welding (GMAW) process stands out as a welding technique widely applicable in various industries, especially in the energy sector. Its versatility for both manual and robotic applications allow for the welding
of different materials and thicknesses in various welding positions. Additionally, GMAW is notable for its excellent deposition rates, control of heat input, and minimal need for cleaning (13–17).

However, despite the remarkable characteristics of the GMAW process, the welding zone (WZ) and the heat-affected zone (HAZ) require particular attention since their development directly influences structural integrity, specifically in mechanical strength and/or fatigue behavior (18–20). Additionally, creating joints in thick-walled components demands a higher heat input, which can pose a challenge in controlling the microstructure in the WZ and HAZ, especially in the coarse-grained heat-affected zone (CG HAZ) (21–23). This zone is located closest to the WZ, experiencing high thermal gradients that increase the cooling rate in this region, leading to reduced fracture toughness and the formation of microstructures such as coarse austenite grains, martensite, bainite and/or high proportions of ferrite side-plates (24–26).

On the other hand, previous studies have shown that the intercritically reheat coarse-grained heat-affected zone (IC CGHAZ) is a critical region within a weld in these materials (27). This area is a part of the CG HAZ reheated by the effect of multiple welding passes and is situated at temperatures between Ac1 and Ac3. In this region, a partial transformation of the austenite phase occurs, which, depending on the cooling rate and the hardenability of austenite, will transform into colonies of pearlite/bainite or residual austenite (RA). The formation of the latter phase is significant due to its association with reduced toughness in the HAZ, even in terms of its distribution and matrix microstructure (28–31). Additionally, the section of the HAZ close to the base metal (BM) is called the subcritical HAZ, which is the region in which the maximum temperature experienced during welding is below the Ac1 temperature of the steel (32).

The addition of microalloying elements, such as vanadium, enables the reduction of bainite colonies and the nucleation of intragranular acicular ferrite due to the low mismatch between vanadium nitrides (VN) and ferrite, leading to a beneficial effect on toughness in the IC CG HAZ (18,33–35).

As mentioned up to this point, the influence of vanadium on the mechanical behavior and microstructural development of HSLA steel joints is an important aspect to analyze in depth. Therefore, this study presents the results of the effect of vanadium addition in thick HSLA steel plates welded with multiple passes using the robotic GMAW process.

**MATERIALS AND METHODS**

**Materials**

In the present work, S355 steel grade (EN10025-2) plates with variations in vanadium content were used as the base metal (BM). The filler metal employed was ER70S-6 (1.2 mm). The nominal chemical compositions of the BM and filler metal are shown in Table 1.

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>CHEMICAL COMPOSITION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>S355 Steel-Base Variant</td>
<td>0.16</td>
</tr>
<tr>
<td>(12 mm thickness)</td>
<td></td>
</tr>
<tr>
<td>S355 Steel-Variant I</td>
<td>0.16</td>
</tr>
<tr>
<td>(15 mm thickness)</td>
<td></td>
</tr>
<tr>
<td>ER70S-6</td>
<td>0.08</td>
</tr>
</tbody>
</table>

**Welding Procedure**

Multi-pass welds were made using a fully automated GMAW process as shown in Figure 1. Single V-groove butt joint configurations were prepared by machining the plates with a 60° groove angle. The GMAW spray transfer mode was employed with a shielding gas consisting of a mixture of 85% Ar and 15% CO2 at a flow rate of 18 L/min. The welding operating parameters are shown in Table 2.
Table 2. Welding operating parameters

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>RUN</th>
<th>Current (A)</th>
<th>Voltage (V)</th>
<th>Welding speed (mm/min)</th>
<th>Heat Input (kJ/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld 1 (Base Variant)</td>
<td>1</td>
<td>120-130</td>
<td>16-17</td>
<td>190-210</td>
<td>0.44-0.56</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>175-185</td>
<td>17-18</td>
<td>240-260</td>
<td>0.55-0.67</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td>170-190</td>
<td>0.75-0.94</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td></td>
<td>370-350</td>
<td>0.39-0.46</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
<td></td>
<td>280-310</td>
<td>0.46-0.57</td>
</tr>
<tr>
<td>Weld 2 (Variant I)</td>
<td>1</td>
<td>125-135</td>
<td>16-17</td>
<td>170-190</td>
<td>0.51-0.65</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>165-175</td>
<td></td>
<td>210-230</td>
<td>0.59-0.72</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td>230-250</td>
<td>0.57-0.67</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td></td>
<td>220-240</td>
<td>0.60-0.73</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
<td></td>
<td>310-330</td>
<td>0.45-0.53</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td></td>
<td></td>
<td>390-410</td>
<td>0.36-0.42</td>
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<tr>
<td></td>
<td>7</td>
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</table>

Arc length: 15-25 mm

Welding Position: 1G

Multi-pass welding with an interpass temperature of 250 °C

**Macro/Microstructural Characterization**

For investigating the macro and microstructural changes resulting from different welding parameters, specimens were prepared using conventional metallographic techniques in accordance with ASTM E3 standard. Nital 2% etching was applied for 10 seconds to assess the macrostructure and microstructure of the joints.

In order to examine the macrostructure, a Nikon SMZ 745T stereoscope was used, while the microstructure was characterized by optical microscope (OM) (Nikon Eclipse LV150) and high-resolution scanning electron microscope (SEM) (FE-SEM Zeiss, Gemini Supra 25).

The microhardness test, using a microhardness tester (HXD-1000TM REMET) with a load of 500 gF, was conducted on the cross-section of the weld, with three microhardness profiles taken: one on the top, another in the central zone, and finally one at the root of the joint. This approach allowed the measurement of hardness values in the BM, HAZ and WZ in each profile.
RESULTS AND DISCUSSION

Macrostructure of Welds
The macrostructural evaluation (Figure 2) demonstrates the achievement a complete joint penetration in both material through thickness. Uniform geometry, no apparent deformations in the base material and no defects such as undercuts, porosities, or hot cracks are detected in the joints. This indicates that the welding parameters employed in this research fall within the appropriate ranges to promote welding integrity.

![Figure 2. Macrostructure of the cross-sections of the welding joints; (a) Weld 1 - Base variant, (b) Weld 2 - Variant I](image)

In each of the welds, the WZ increases in size as the heat input rises. Figure 2(a) represent a weld with smaller size at the top compared to Weld 2 (Figure 2(b)); however, the latter exhibits a smaller size at the weld root. This could be attributed to the lower thermal mass of Weld 1, which has lower thickness. Where the applied heat has a more concentrated impact, leading to increased fusion and penetration in the WZ, resulting in larger root weld size.

Microstructure of Welds
Figures 3 to 10 show the microstructural evolution in different welding zones of the joints. It is possible to observe in each micrograph the various areas of the HAZ, which are described as the subcritical HAZ (Figure 3 and Figure 7), closest region to the base metal and, in turn, the farthest from the WZ. Next to this, there is the IC HAZ (Figure 4 and 8), and finally, the CG HAZ (Figure 5 and 9), which is the nearest region to the WZ.

![Figure 3. Subcritical HAZ (Weld 1 - Base variant); (a) OM, (b) SEM](image)
Figure 4. IC HAZ (Weld 1 - Base variant); (a) OM, (b) SEM

Figure 5. CG HAZ (Weld 1 - Base variant); (a) OM, (b) SEM

Figure 6. Welding zone (Weld 1 - Base variant); (a) OM, (b) SEM
Figure 7. Subcritical HAZ (Weld 2 – Variant I); (a) OM, (b) SEM

Figure 8. IC HAZ (Weld 2 – Variant I); (a) OM, (b) SEM

Figure 9. CG HAZ (Weld 2 – Variant I); (a) OM, (b) SEM
Both microstructures welded samples reveal the presence of martensite, bainite and retained austenite (RA) through the different areas of the HAZ, while in the subcritical HAZ a carbon dissolution within the ferritic-pearlitic transformation occurs. Furthermore, the IC HAZ of Weld 2 exhibits finer grain size compared to Weld 1. These achievements determines that the vanadium addition leads to grain refinement, which is known to be beneficial to toughness and fatigue resistance (36).

The WZ (Figures 6 and 10) presents a dendritic structure, with some grain refinement areas, due to the remelting effect generated by the deposition of the multiple weld beads.

Microhardness of Welds
The hardness behavior in both welds is depicted in Figures 11 and 12, for the base variant and variant I respectively, showing some variations in different zones of the joint compared to the values of the BM. In Figure 11, an increase in hardness is observed in the HAZ (210-215 HV0.5) respect to the BM and the WZ (180-190 HV0.5) in the upper, center, and root of the joint.

In Weld 2 (Figure 12), the HAZ in the upper part of the weld exhibits a maximum hardness value of 330 HV0.5, while decreasing to 230 HV0.5 and 210 HV0.5 as one descends to the central and root parts of the joint, respectively. This behavior can be attributed to various factors such as grain size, residual austenite formation, and/or the diverse heat transfer modes occurring in each region of the welded joint. Since this joint undergoes high heat input in the upper welding passes, the thermal gradient in this zone with respect to the surrounding environment is higher, influencing the cooling rate.

An important aspect in this weld is of broad interest as the HAZ-root exhibits hardness values without significant variation compared to the BM and the WZ, which may contribute to improved mechanical performance. Additionally, despite the high heat input in this welding area due to continuous reheating, the hardness values remain consistent, even approaching those reported in Weld 1. This indicates a positive influence of vanadium on the variation of this property.

Although the relationship between weld hardness and fatigue behavior requires a more detailed analysis, the obtained results are of great significance. Avoiding stress concentrators caused by excessive hardness, especially in the HAZ, is crucial to improve the fatigue resistance of the welding joint. A future study will focus on evaluating the fatigue behavior of this joint. Previous and complementary research (35) has demonstrated that as the vanadium content increases and combines with the formation of a bainitic microstructure, fine precipitates, and/or the presence of residual austenite in brittle zones such as the HAZ, it is possible to increase mechanical strength while maintaining an appropriate ratio between yield strength and maximum load (YS/UTS). Additionally, it has been observed that fatigue resistance, especially under conditions of a low number of cycles to rupture, improves with the presence of this microalloying element.
Figure 11. Microhardness HV0.5 measurement in Weld 1 – Base variant

Figure 12. Microhardness HV0.5 measurement in Weld 2 – Variant I
CONCLUSIONS

This study presents the results of the influence of vanadium as a microalloying element in the weld joint of high-thickness S355 steel using the robotic GMAW process with multiple passes. Various zones of the weld were analyzed microstructurally and subsequently, through the hardness test, a general assessment of its influence on the mechanical behavior of the joint was conducted. The following conclusions summarize the findings:

- Both welds exhibit uniform geometry throughout the weld bead, with no presence of pores, cracks, or lack of fusion/penetration.
- Weld 2 (with vanadium addition) shows a smaller dimension at the root despite having a higher heat input compared to Weld 1. This is attributed to the higher thermal mass of the plate in Weld 2, where the applied heat has a less concentrated impact, leading to greater heat transfer, reducing fusion and penetration in this weld zone.
- The addition of vanadium does not significantly influence the microstructural development. In both welds, we have observed a coarse-grain HAZ and a variation a change of the microstructure from bainite to ferrite-pearlite, irrespective of the considered chemical composition. However, grain refinement is observed in the intercritical HAZ of the Weld 2, alloyed with vanadium, suggesting a possible beneficial effect on toughness specially at higher heat input.
- Microhardness evaluation demonstrate that the HAZ at the root of Weld 2 maintains hardness values without significant variation compared to the BM and the WZ. Despite the high heat input, these values remain close to those reported in Weld 1, indicating that vanadium does not lead to a higher hardness on the HAZ, when compared to the base material. This suggests that vanadium could be beneficial for toughness and fatigue properties in the root of the welded joint.

REFERENCES


