Study of structure and physico-mechanical properties of welding joints on vessel tank of austenite steel SS316

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Abstract. The article addresses some problems related to the occurrence of cracks and defects in welding joints on a horizontal steel vessel tank after machine gas metal arc welding (GMAW). Tests have been carried out on the structure and mechanical properties of the welding joints between the cylinder and elliptical bottoms made of austenite steel SS316 according to AISI (X5CrNiMo17-12-2 according to BDS EN 10088-2). Proven methodologies of microstructural and X-ray analysis were used to investigate the changes in the structure (weld seam, heat affected zone and base metal). The mechanical characteristics are determined by measurements of macro- and micro-hardness by Vickers and of static tension.

1. Introduction

Radiographic inspection of welding joints after machine gas metal arc welding (GMAW) of a vessel tank [1] of austenitic SS316 steel reveals some cracks. The vessel tank is a horizontal cylindrical vessel closed on both sides with elliptical bottoms of diameter D=1.2m and length L=2.0m (Figure 1). The hull thickness is 3mm. The vessel tank is supported by two saddle posts welded to the cylinder.

![3D model of a vessel tank made of austenite steel SS316](image)

Figure 1. 3D model of a vessel tank made of austenite steel SS316

The elements of the vessel tank [2] that are in contact with the working fluid in it are made of austenite steel SS316, and the saddle supports are made of carbon steel. Upon completion of the welding, they are primed with a zinc-rich primer. The vessel [3, 4, 5] is externally insulated from the environment by thermal insulation 100mm thick, since the fluid stored therein is water at a temperature of 7°C [5].
2. Essence of analysis
In order to determine the causes of cracks and defects in the welding joints, samples of austenite steel SS316 are prepared. The chemical composition of the steel (SS316) used for the purposes of this study is shown in Table 1[6, 7].

| C   | Si  | Mn  | P   | S   | Cr  | Ni  | Mo  | N   |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.07| 1.00| 2.00| 0.05| 0.03| 16.5-18.5 | 10.0 - 13.0 | 2.0 - 2.5 | 0.11 |

The GMAW of the samples is carried out with ESAB OK Autrod 316LSi stainless steel wire BDS EN ISO14343-A: G 19 12 3 LSiSFA/AWS 5.9: ER 316LSi [8, 9] with diameter of the wire Ø0.8mm. This wire has good resistance to intercrystal corrosion and general corrosion in wet environment up to a temperature of 400°C, as well as resistance to weld scale formation up to 800°C [6, 8, 10].

The typical chemical composition and mechanical characteristics of the metal of the weld seam are shown in Table 2 [11].

| C   | Si  | Mn  | Cr  | Ni  | Mo  | Tensile strength, Rm MPa | Yield strength, Re MPa | Total elongation | Impact energy, KV J/°C |
|-----|-----|-----|-----|-----|-----|--------------------------|------------------------|-------------------|----------------------|
| <0.03 | 0.80 | 1.90 | 19.0 | 12.0 | 2.70 | 620 | 440 | 37 | +20 | -60 | -196 |
|      |     |     |     |     |     |    |    |    | 120 | 95  | 55  |

Welding is performed with a semi-automatic welding machine in the following modes [12]:
- DC and polarity (+);
- Protective gas M13 ~ 96% Ar (argon) + 4% O₂ (oxygen).
- Protective gas consumption - Qw = 12 [l/min];
- Current- I=55-160 [A];
- Voltage- U=12-24 [V];
- Welding velocity- Vw=4-17 [m/min];
- Wire feed velocity- Vwf=15 [m/min];
- Melting performance- H=1.0-4.1 [kg/h].

After the GMAWof the cylinder to the elliptical bottoms, two samples of the problem areas are cut out: Sample I and Sample II as is shown in Figure 2.

![Cylinder](image1)
![Bottom](image2)
![Inside view](image3)
![Outside view](image4)

**Figure 2.** Macro images of the cut samples for testing: a- Sample I; b – Sample II.
For the purposes of this study, the samples were polished [13] with a water sandpaper, then the polished surfaces were treated with an acid solution between nitric and hydrochloric acid in a ratio of 3 to 1. A metallographic microscope NEOPHOT 2 [13] was used for observation with different magnifications of the macro and microstructure with a device Haneman 100 attached to it. The Vickers method (HV0.05 and HV5) [14] was used to measure the hardness of the samples in the different welding zones. The phase composition of the samples was determined with X-ray apparatus model DRON 4. A stereo-microscope for macro-examination EUROMEX was also used in the analysis.

3. Macrostructure of polished samples

Figure 3a and 3b show macro images [13] of the polished samples with notations of the different zones in the structure obtained after GMAW with the OK Autrod 316LSi electrode.

![Macrostructure of polished samples](image)

**Figure 3.** Macro-structure of the polished samples after GMAW with OK Autrod 316LSi electrode: a – Sample I; b – Sample II.

4. Microstructure of polished samples

From the metallographic analysis of the structures using a NEOPHOT 2 metallographic microscope [13], images were obtained from the different zones of the samples. Figures 4 and 5 show the microstructures of the two samples at magnification 400 times and the locations with the measured microhardness HV0.05 in depth of the samples.

![Microstructure of polished samples](image)

**Figure 4.** Microstructure of welding joint at magnification 400 times for Sample I: a – Base Meral Zone; b – Weld Metal Zone; c – Alloying zone.
The microstructural analysis of the different zones in the two samples reveals that the structure of the base metal and the weld seam material is austenitic with traces of textured ferrite. Deformation stripeness is registered in the inner zones. The visual control and microscope observation of the weld seam material do not detect any gas or non-metal defects caused by the welding.

5. Macro-hardness by Vickers
After the metallurgical analysis of the structure, macro-hardness [14] was investigated in the different zones of the samples, using the NEOPHOT 2 metallographic microscope for this purpose. The values were recorded in the depth of the samples and are digitally indicated in Figure 6-a, for Sample 1 and in Figure 6-b for Sample 2.
6. Micro-hardness by Vickers.

Figures 7 and 9 show the locations and the recorded value of the measured Vickers micro-hardness $HV_{0.05}$ [14]. The figures show that lower or the same hardness is registered in the weld seam material relative to the hardness of the base material.

Thus, to better illustrate the results obtained from the measured micro-hardnesses $HV_{0.05}$ in two samples, graphical dependencies are shown in Figure 8.

![Image of Figure 7 and Figure 8](image)

**Figure 7.** Micro-hardness $HV_{0.05}$ for Sample 1: a and b base metal zone; c - weld metal zone; d and e - alloying zone

**Figure 8.** Graphical representation of the results from the measured micro-hardness $HV_{0.05}$ for Sample I and Sample II in the different zones.
7. X-ray structural phase analysis
The X-ray structural analysis is one of the most commonly used methods for testing the fine structure of metals. It is based on the ability of X-rays to diffract from crystalline objects that serve as a diffraction grating. For the purpose of this study, an X-ray structural analysis has been made of the welded samples and of some additionally prepared control samples of austenite sheet steel SS316. The purpose was to determine the phase composition in the steel before and after welding with the selected GMAW mode and type of electrode.

From the analysis thus made using the X-ray apparatus model DRON 4, it is clear that the base material and that of the weld seam have phases of the same type, which are mainly austenite and ferrite (Figures 10 and 11).

Figure 9. Micro-hardness HV0.05 for Sample 2: a and b base metal zone; c - weld metal zone; d - and e - alloying zone

Figure 10. X-ray structural analysis of sheet steel SS316
Figure 11. X-ray structural analysis of the welded sample

8. Static tension test of the welding joint

The mechanical properties are of great importance in the production of welding joints. That is why the object of our study was testing the tensile strength of two types of welded samples. For this purpose, 6 laboratory tubes, 3 for each of the two tested sections of the vessel tank were prepared and pre-welded according to the described procedure. They were subjected to static tension with a laboratory tension/compression machine according to BDS EN ISO 7500-1:2016.

The tested samples with their fracture locations indicated are shown in Figure 12. The results of the static tension test of welded joints and sites with fracture zones are shown in Table 3.

![Figure 12. Sample bodies after tension test: a - Sample I; b - Sample II.](image)

Table 3. Results from the static tension tests on the welding joints

| №  | Tested samples | Measured values of controlled parameters |
|----|----------------|-----------------------------------------|
|    | Sizes* mm,    | Tensile strength, Rm, N/mm²    | Location of destruction |
| Sample I-1 | 3.0x19.8 | 615 | In base metal |
| Sample I-2 | 3.0x20.5 | 618 | In base metal |
| Sample I-3 | 3.0x21.2 | 603 | In base metal |
| **Measured** (average value): | | **612** | - |
| Sample II-1 | 3.0x21.0 | 489 | In weld joint |
| Sample II-2 | 3.0x19.3 | 620 | In base metal |
| Sample II-3 | 3.0x20.5 | 618 | In base metal |
| **Measured** (average value): | | **576** | - |
| **Required:** for steel 316 accord. | | **500-700** | - |

To AISI X5CrNiMo17-12-2 accord. To BDS EN 10088-2 material 1.4401.

From the tension tests carried out on sample I, it was established that destruction occurs outside the welded joint in the zone of the vessel tank. With Sample II, of the three tension test tubes, only one was destroyed at the welded joint. The cause has been identified and it is due to the displaced and open root of the seam, which indicates the lower strength of the seam material.
9. Conclusion
After the machine GMAW of a vessel tank of austenite steel SS316, the following problems have been diagnosed in the two tested control sections:

✔ For Sample 1:
   The root of the seam has penetrated into the wall at the bottom, probably as a result of incorrect positioning of the semi-automatic device, with the profile of the seam not well shaped. As a result of axial and radial stresses, deformation occurred at the point of contact between the cylinder and Bottom 1, which caused cracks to appear symmetrically located at the root (Figure 2 a). In the cross-section of the seam, these cracks also developed in the material of the seam when it was in a liquid and highly plastic state.
   There are no gas and slag defects registered in the seam material; it is the evidence of correctly selected modes and the technology of GMAW.

✔ For Sample 2:
   The profile of the seam in the tested section is well shaped but again displaced, this time in the direction of the cylinder, due to which part of the contact zone between Bottom 2 and the cylinder is not alloyed; the penetration into the material at Bottom 2 is weak, and into the cylinder it is incomplete. As a result, the root of the seam has a large open surface.

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