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# Evaluation of High Strength Low Alloy Carbon Steel Produced with Wire Arc Additive Manufacturing Technology and its Possible Application in the Oil and Gas sector

## (Avaliação do Aço Carbono Baixa Liga de Alta Resistência Produzido com Tecnologia de Manufatura Aditiva por Arco Elétrico e sua Possível Aplicação no Setor de Petróleo e Gás)

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## Abstract:

Wire Arc Additive Manufacturing (WAAM) is gaining increased focus in several industries and particularly in the Oil & Gas sector. This technology is often considered as a competitive and lead-time effective Additive Manufacturing (AM) process to produce large metallic components. This paper focuses on low alloy high strength carbon steel, widely used on top side and surface O&G applications, currently produced with forged SAE 4140-like materials or equivalent. The aim of this paper is to present the results obtained on low alloy high strength carbon steel material produced by WAAM. The results are presented including both 'as-built' and 'post heat treatment' conditions. Furthermore, considerations are developed regarding non-destructive evaluations of such WAAM material. Finally, a discussion is proposed considering potential applications of the technology for Oil & Gas sector.

**Keywords:** Wire Arc Additive Manufacturing, High Strength Low Alloy Carbon Steel, Mechanical properties, Non-destructive Testing, Oil and Gas

# 1 INTRODUCTION

Additive manufacturing (AM) has been widely investigated for the fabrication of metallic parts with complex shapes. In contrast to the conventional manufacturing processes, AM is *"the process of making a three-dimensional solid object from a computer-aided design (CAD) model, for which successive layers of material are laid down in different shapes, without using tooling or even support materials"* [1].

Furthermore, and contrary to the traditional process of material removing, additive manufacturing offers the possibility to only add material where it is needed resulting in reduced raw material consumption and potential redesigning; ultimately contributing to a more environmentally friendly manufacturing.

*Wire Arc Additive Manufacturing (WAAM)* is a directed energy deposition (DED) AM process that adopts metallic wire as feedstock material and electric arc as energy heat source. WAAM is receiving more and more attention from industry as it enables higher deposition rates than other DED processes (laser, electron beam). Furthermore, it is a relatively low-cost system for the production of large parts (up to 2 cubic meters) with low to medium complexity shape or for the addition of structural details to semi-finished parts.

For several years now, Vallourec has embarked in a collaborative journey to demonstrate the suitability of WAAM for various O&G components. As an illustration, 2 years ago, Vallourec joined a Joint-Innovation-Project (JIP) led by DNV-GL and Berenschot which aimed to release a guideline for the qualification of Additive Manufacturing (AM) components for the Oil & Gas and Maritime industry [2]. In parallel to its various collaborations, Vallourec has also developed a dedicated R&D program in order to increase knowledge on the effect of WAAM process parameters on product properties aiming to provide AM parts compliant with the target application specifications.

This paper aims to present the recent researches performed by Vallourec on carbon-steel produced by Wire Arc Additive Manufacturing. Two WAAM strategies were defined and then compared, especially with regards to defect density and sizes through non-destructive testing and mechanical properties. The most interesting strategy was then more extensively characterized through mechanical, metallurgical, and chemical analysis both in as welded and heat-treated conditions to assess performance of such material.

# 2 MATERIALS AND METHODS

## 2.1 MATERIAL

Vallourec has performed a benchmark of existing carbon steel wire feed stock in order to choose a suitable candidate for the production of high yield strength WAAM components (up to 125ksi grade). Finally, wire was selected according to AWS A5.28 ER120S-G. WAAM parts were produced on a base plate in S355. Chemical composition of the feedstock wire used is summarized Table 1. An Ar-$CO_2$ shielding gas (18 vol.% $CO_2$) was used to protect the fusion zone during deposition.

|  | C | Si | Mn | Cr | Ni | Mo |
|---|---|---|---|---|---|---|
| Solid Wire | <0.1 | 0.25-0.60 | 1.4-1.8 | <0.6 | 2.0-2.8 | 0.30-0.65 |

*Table 1: chemical composition of the wire feedstock AWS ER120-G (mass %)*

## 2.2 PROCESS PARAMETERS

A six-axis robot arm was used to deposit material using two different strategies based on GMAW welding process. After an optimization loop to screen welding parameters, two sets of parameters were defined and summarized in Table 2.

|  | Wire feed speed (m/min) | Travel speed (cm/min) | Current (A) | Voltage (V) | Gas flow rate (l/min) | Wire size (mm) |
|---|---|---|---|---|---|---|
| Strategy 1 | 3 | 55 | 170 | 19 | 20 | 1.2 |
| Strategy 2 | 7.5 | 90 | 221 | 26.7 |  |  |

*Table 2: WAAM deposition parameters of the 2 defined strategies*

## 2.3 HEAT TREATMENT

A heat treatment composed of austenitizing, quenching and tempering was applied on strategy 2.

## 2.4 COMPONENTS SHAPE

Components produced were tubular, with variable outer diameters within the range of 4in to 14in (102 mm to 356mm) , and with a wall thickness variation within the range of 15mm to 80mm. Figure 1 illustrates typical component geometry and Figure 2 shows an example of a part during production.

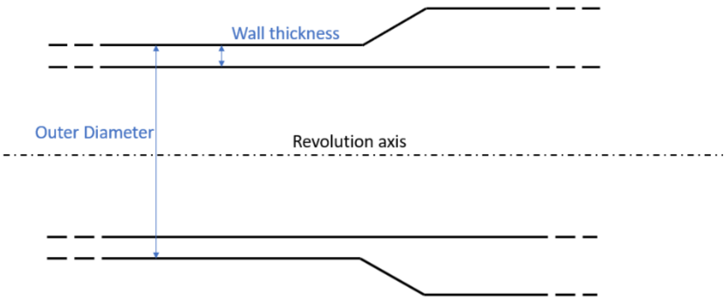

*Figure 1: Typical geometry of the produced WAAM components*

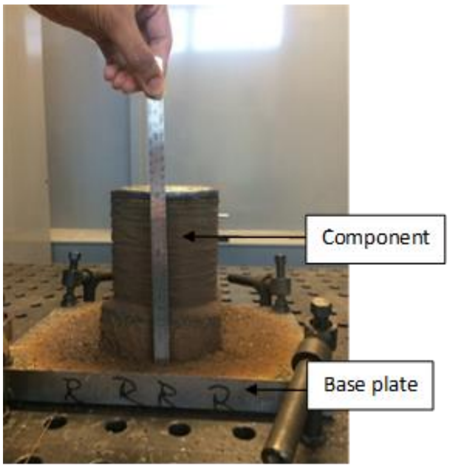

*Figure 2: Example of component in production*

## 2.5 TEST CONDITIONS

### 2.5.1 Non-destructive characterizations

Many different Non-Destructive Testing (NDT) methods are available in the industry, each of them having their own advantages, limitations, and maturity of development. Even if the defects observed on WAAM components are different from the ones observed on hot-rolled or forged components, it was decided to refer to the criteria used on forged components in the Oil & Gas field as a starting point.

For the inspection of WAAM materials, a combination of two complementary techniques was used to assess the quality of the finished products: magnetic particle inspection (MPI) and ultrasonic testing (UT). These two techniques are complementary since MPI allows an accurate examination of the surface while UT provide fine inspection of the core of the component. A rough machining of the parts was performed to get a smooth surface (Ra < 32µm) needed for an accurate NDT inspection.

#### *2.5.1.1 Magnetic Particle Inspection (MPI) for superficial analysis*

Magnetic Particle Inspection is widely used within the O&G field for the control of surface defects. It is a very effective method for the detection of surface breaking and slight sub-surface defects such as cracking, pores, cold lap, lack of sidewall fusion in welds and therefore in products made from additive manufacturing processes. The most versatile technique is using a handheld electromagnetic yoke magnet, a white strippable paint as a contrast background and a magnetic "ink" composed of iron powder particles in a liquid carrier base. The tested area is magnetized with the yoke magnet. In the event of a surface or slightly sub surface defect being present, the lines of magnetic force will deform around the defect. The magnetic ink is applied, and the iron powder particles will concentrate in areas with higher magnetic field, meaning around defects that induce magnetic flux leakage and give a visible indication against the white contrast background.

The criteria applied was based on M2 criteria defined in NF EN ISO 10893-5 [3] - usually applied for the control of forged components within the Oil&Gas industry - which is summarized on Table 3**Error! Reference source not found.**.

| Criteria | Frame aperture | Max number of defects in the frame | Max length for single defect |
|---|---|---|---|
| M2 | 100mm * 150mm | 8 | 6mm |

*Table 3: Maximum permissible number of indication and dimensions (diameter or length) within the specified frame, for a wall thickness between 16mm (excl.) and 50mm (incl.).*

#### *2.5.1.2 Ultrasonic Testing (UT) for the inspection of volumes*

Two type of UT inspections were performed:

- An inspection using high sensitivity for both strategies to compare the density of defects between the two strategies in an as welded state.
- An inspection after calibration to assess the criticality of the defects revealed for both strategies.

In order to calibrate the UT inspection and to define the detection threshold, 6.4mm flat bottom holes are often used within the O&G industry for NDT threshold calibration. In order to be more conservative, the calibration was performed on 3.2mm flat bottom holes.

### 2.5.2 Destructive characterizations:

Various characterizations were performed on both as welded and heat-treated states:

- **Tensile test** at room temperature on cylindrical specimens with 4.06mm and 6.35mm diameters. Samples were cut at mid-wall on two different orientations (see Figure 3): longitudinal (parallel to build direction: PBD[1]) or transverse (parallel to deposition path[2] i.e. normal to build direction: NBD).
- **Impact test** at 0°C on Charpy V-notched specimen 10x10mm² cut at mid-wall on both orientations.
- **Hardness quadrants**: 12 points quadrants using Vickers indenter at 10 kg force / 98N with 4 points per position:
  - 1.5mm from inner surface (ID, stand for Internal diameter)
  - mid-wall (MW)
  - 1.5mm from outer surface (OD, stand for Outside Diameter)
- **Microstructure**: standard polishing then nital 3% etching

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[1] Build direction refers to the direction of superposition of layers

[2] Deposition path refers to the orientation of the bead

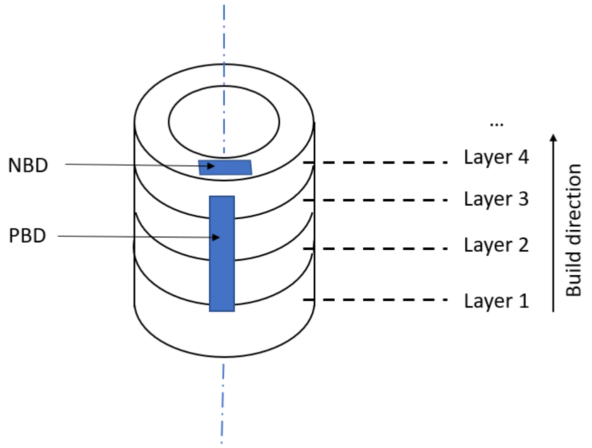


*Figure 3: Wording used to define the orientation of the specimens – according to DNV-GL guideline [2]. NBD: normal to building direction. PBD: Parallel to building direction*

# 3 RESULTS

## 3.1 NON-DESTRUCTIVE TESTING

Non-Destructive Testing was performed for both strategies to assess the influence of the strategy on final part defectology.

### 3.1.1 Magnetic Particle Inspection

MPI was performed on as-welded materials. On each part, only a few defects above the criteria defined in 2.5.1.1 were observed. An example of a defect above 6mm is shown on Figure 4. Grinding repairs allowed by Oil&Gas norms such as API 5CT [4] were performed to remove these defects. As same defects were observed for both strategies, MPI was not a criterion to assess which one was the best in terms of surface defects.

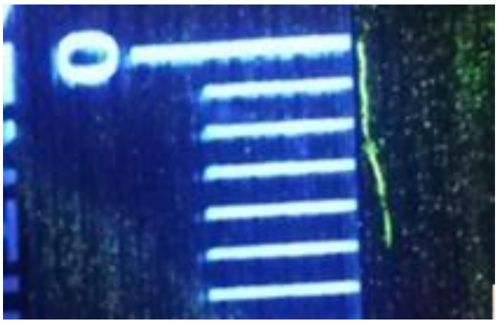
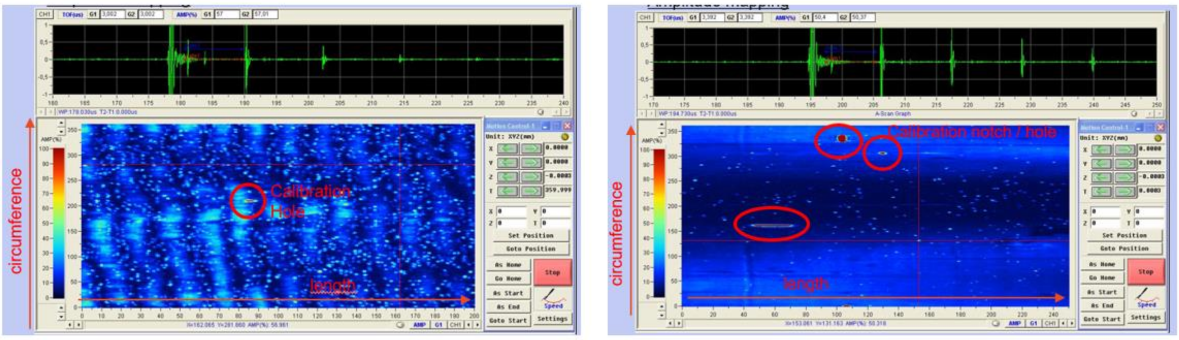


*Figure 4: Example of surface defect revealed by MPI. These defects could be local cracks or lack of material after machining.*

### 3.1.2 Ultrasound testing

#### *3.1.2.1 Highly sensitive control*

A first inspection without calibration was performed on the as welded states. Examples of results are shown on Figure 5.



**Strategy 1** **Strategy 2**

*Figure 5: Results obtained by ultrasound testing on strategy 1 and strategy 2. Amplitude 45dB. Calibration notches and holes are marked in red but were not used for the high sensitivity control. Strategy 1 shows more small indications (amplitude <60%) than strategy 2.*

Strategy 1 shows a higher density of small-size indications as compared to strategy 2, which highlights the impact of the strategy on the defects rate.

#### *3.1.2.2 Calibrated inspection*

Both strategies were then inspected after calibration on 3.2mm notches and flat bottom holes. After calibration, no indication was revealed for both materials. Even if some small indications were revealed by sensitive inspection, these parts were fully compliant according to the chosen calibration criteria, widely used to control forged components.

### 3.1.3 Conclusion on Non-destructive testing

MPI did not highlight significant difference between both strategies and although some defects were observed, these defects were repaired by grinding as allowed by API 5CT norm [4].

Although both strategies were compliant according to the criteria used (3.2 mm flat bottom holes and notches), it was decided to conduct mechanical characterization on strategy 2,presenting much less small indications, to assess the performance of the material through mechanical testing both in as welded and heat treated conditions.

## 3.2 *TENSILE PROPERTIES*

Tensile tests were performed at room temperature in an as-welded state and after heat treatment. Results are summarized in Figure 6.

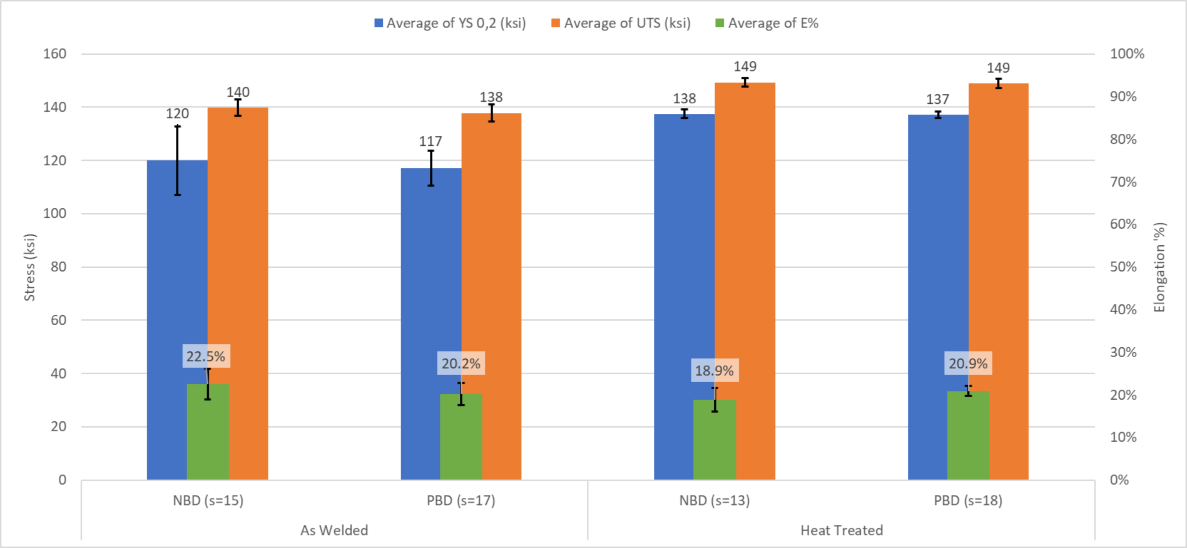


*Figure 6: Tensile results obtained in as welded and heat-treated conditions – The numbers on the graph are the average values. The standard deviation for each population sample are marked in black lines – PBD: Parallel to Build Direction / NBD: Normal to Build Direction / s = number of specimens*

As-welded results show a good yield strength at room temperature between 117 and 120 ksi depending on the orientation. However, standard deviation on yield strength reaches 13ksi which highlights the heterogeneity of as deposited material. Impact of the orientation is relatively low with a variation on average of only 3ksi. Elongation is above 20% which shows a good ductility.

After heat treatment the average yield strength increased up to 137ksi with a significant reduction of the standard deviation down to 3ksi, highlighting a better homogeneity of the heat-treated material. The effect of the orientation is also reduced to 1 ksi variation on the average yield strength values, which highlights a low anisotropy. The material is still ductile with an elongation above 18%.

On UTS, we notice small standard deviations and an increase of about 10ksi with the heat treatment. There is no significant impact of the orientation on average UTS, with a variation of 2 ksi from NBD to PBD as welded and no variation after heat treatment.

## 3.3 IMPACT PROPERTIES

As welded and heat-treated materials were first investigated at 0°C, the results are presented on Figure 7. For the part showing the lowest values, additional tests were performed at 20°C (see Figure 8).

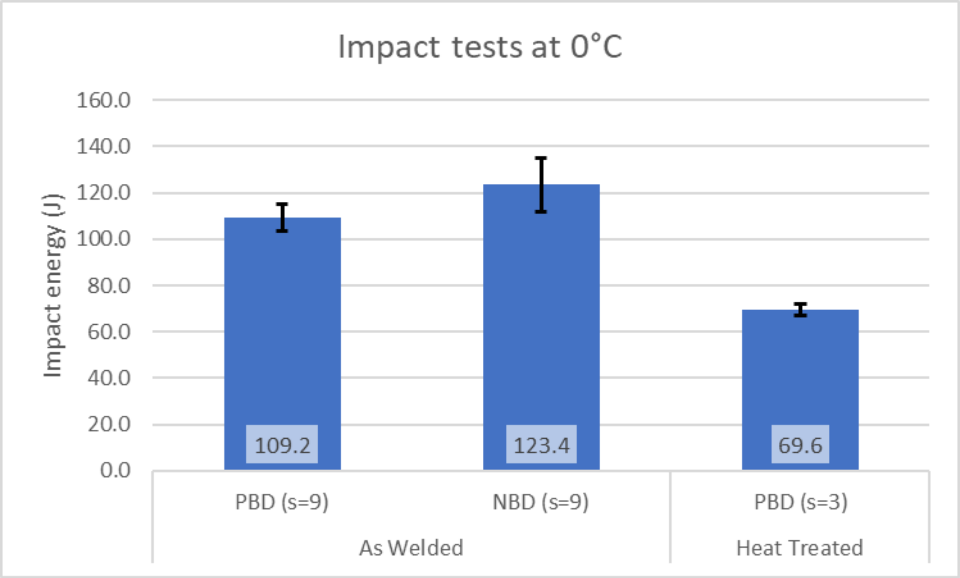


*Figure 7: Impact tests results obtained at 0°C in as welded and heat-treated condition. The number on the graph are the average values. The- standard deviation for each population sample are marked in black lines - PBD: Parallel to Build Direction / NBD: Normal to Build Direction / s = number of specimens*

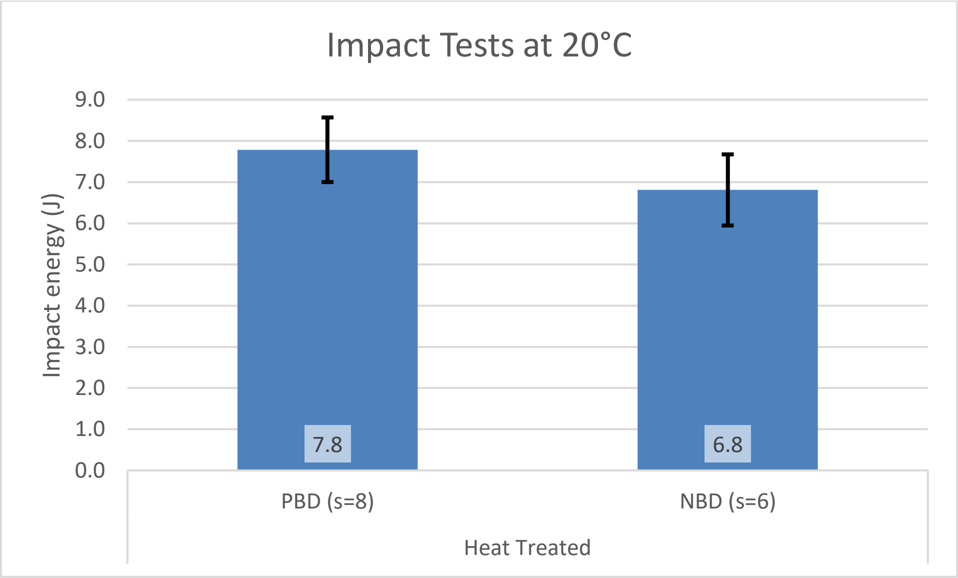


*Figure 8: Impact results obtained at 20°C in heat treated condition - standard deviation for each population sample are marked in black - PBD: Parallel to Build Direction / NBD: Normal to Build Direction / s = number of specimens*

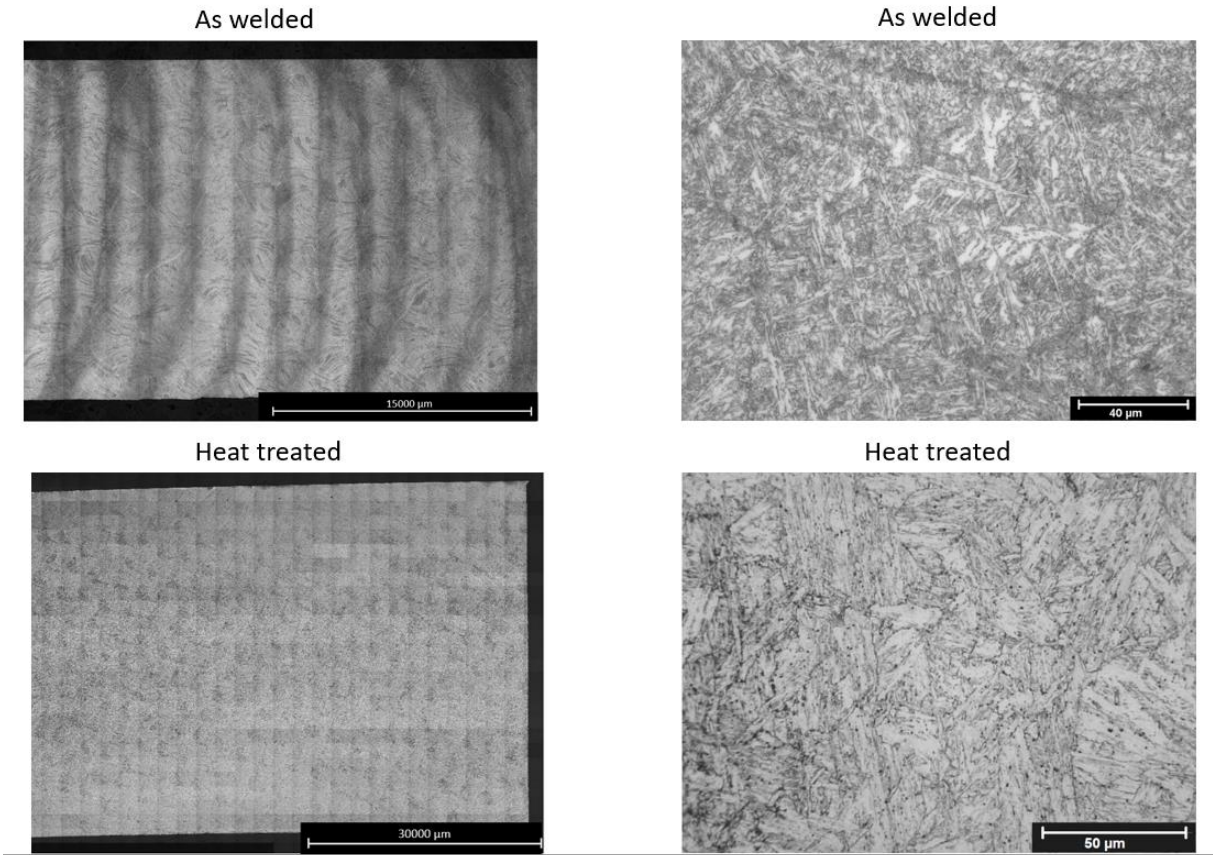
Average on as-welded impact test at 0°C shows a limited impact of the orientation on the measured energy. No significant impact of the orientation can be observed on the heat-treated state at 20°C either.

The average impact energy after heat treatment of 70J at 0°C is quite honorable for a 137ksi-yield strength WAAM material but is about 30% lower than in as-welded condition. This is linked to the increase of tensile properties brought by heat treatment that often leads to a reduction of the impact energy for carbon steels.

## 3.4 MICROSTRUCTURE

Microstructure in the as-welded condition shows a fine microstructure, mostly martensitic and with clearly defined weld beads (see Figure 9).

After heat treatment, weld beads are less visible and the observed microstructure - mainly tempered martensite - is quite homogeneous through wall thickness.


As welded

As welded

Heat treated

Heat treated

*Figure 9: Microstructure observation as welded and after heat treatment – Nital 3% etching*

## 3.5 HARDNESS

Hardness points were performed as welded and after heat treatment close to the outer diameter, at mid-wall or close to inner diameter of the part produced.

Hardness measurements show a good homogeneity through wall either on as-welded state and on heat-treated state, with limited variation on mean values for different positions in thickness, less than 10HV (see Figure 10).

The hardness value after heat treatment is about 350HV10, which is 50HV higher than in the as-welded state and are in agreement with the higher tensile properties observed after quenching and tempering.

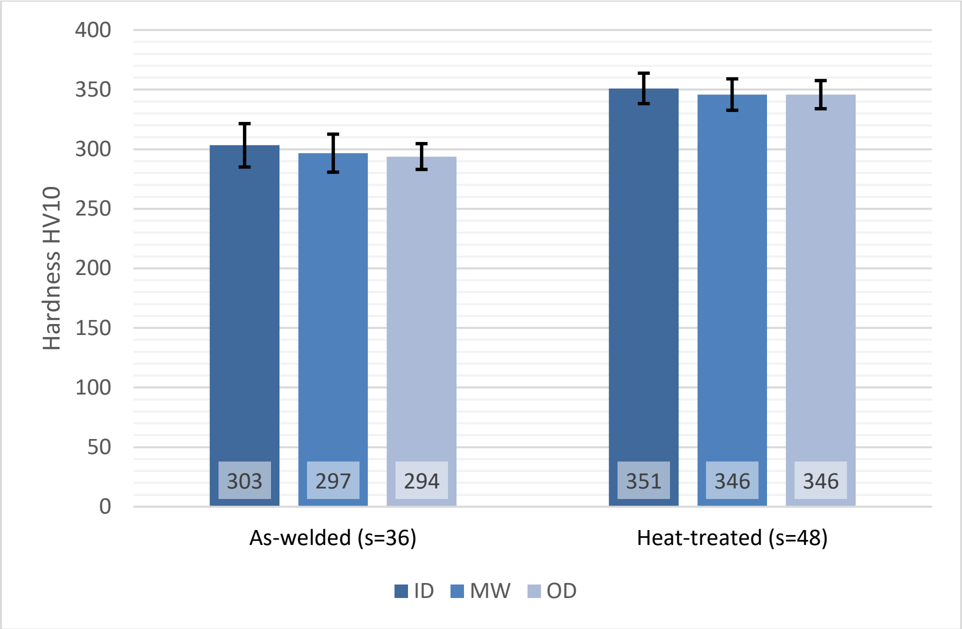


*Figure 10: Average HV10 hardness values measured for different position in the thickness (ID= Inner Diameter, MW= Mid-wall, OD= Outer Diameter). Global standard deviations: as welded σ=15 HV10 / heat treated σ=13 HV10 / s = number of specimens*

# 4 CONCLUSION

Two sets of GMAW welding parameters were used to produce material using AWS A5.28 E120S G wire.

Non-destructive tests helped to define the best strategy to be further investigated. Ultrasound testing clearly highlighted a lower number of indications for strategy 2. With regard to Magnetic Particle Inspection (surface NDE), both strategies have shown surface defects above an M2 acceptance criterion. These defects could be repaired using grinding as commonly practiced in industries. Finally, both strategies were inspected using calibrated reference defects and showed that both materials are in line with the defined criteria.

Based on the former results, strategy 2 was further investigated in as welded and heat-treated state.

Even if the mechanical results of the as-welded product were encouraging with an average yield strength of about 117ksi, heat treatment improved the average yield strength up to 137ksi and led to a better homogeneity of the tensile property along different orientations. Although lower than in as-welded state, the impact energy after heat treatment was still around 70J at 0°C. At 20°C, the values are still around 70J with very small differences along different orientations.

After heat treatment, microstructure - mainly tempered martensite - and hardness values also highlighted a good homogeneity through wall thickness, with less than 10 HV10 difference between inner and outer surface of the wall.

Based upon the positive results and promising opportunities of the WAAM technology, further developments and research activities are on-going, particularly with regard to fatigue and corrosion evaluations.

# 5 PERSPECTIVES FOR THE OIL&GAS MARKET

Thanks to its high deposition rate, WAAM is one of the most cost-effective Direct Energy Deposition process. It enables the manufacturing of near net shape parts with low to medium complexity shape. Leveraging on decades of welding expertise and experience, Wire Arc Additive Manufacturing is a versatile, efficient, and robust process, which places it as one of the most attractive Direct energy Deposition technics and the reason for a growing industrial interest.

The results revealed by this study highlighted opportunities to produce large carbon steel components with appropriate yield strength properties. The oil and gas industry uses carbon steel materials, particularly low- or un-alloyed steels for various applications such as: Valves, Flanges, Couplings, Shaftings, Fixtures, etc. While there are still some researches to be done on WAAM performance, particularly with regards to its qualification for downhole and subsea critical performance, this study provides evidence of an acceptable level of performance for a number of applications. Among them, surface components like test caps or test plugs and various mud circulating tools are some of the first components that may be used on the field in the near future. To illustrate the case, among the different studies conducted during the development of the Guideline with DNVGL, Vallourec led the production of a full scale component with the objective to increase the technology readiness level (TRL) of WAAM and to demonstrate its suitability for certain applications. The component was successfully tested up to 9,000 psi internal pressure (see Figure 11).

*Figure 11: Picture of a circulating head produced by WAAM during the development of the DNV-GL guideline* [2]*. Manufacturing and tests were led by Vallourec. Length about 1.2 meters.*

Typical requirements for such components are summarized on Table 4.

| Category | Description | Acceptance/Rejection Limits |
|---|---|---|
| Tensile Test | Yield Strength (ksi) | 125-140 |
|  | Min. Ultimate Tensile Strength (ksi) | 135 |

|  |  |  |
|---|---|---|
|  | Min. Elongation (%) for round tensile specimen with phi=4.06mm | 8.5% |
| Impact test | Charpy V-notch<br>Transversal at 0°C | Specimens size 10x10mm<br>Min. Sing. value: 27J |

*Table 4: Typical requirements on tensile and impact properties for O&G accesories*

# 6 ACKNOWLEDGMENTS

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