1. Introduction

Wire and Arc Additive Manufacturing (WAAM) is an emerging fabrication process that has been gaining significant attention in Brazil and worldwide due to its ability to produce complex parts with intricate and customized geometries, combining materials and mechanical properties (Galeazzi, 2024).

This process focuses on the full manufacturing or composition of component parts through the controlled deposition of material along a predefined path, where fusion is achieved via the action of an electric arc. In the GMAW (Gas Metal Arc Welding) process, the electric arc is established between the substrate and a consumable wire electrode. This wire is continuously fed by the welding torch and melted by the arc, depositing material in a controlled manner as it moves along the travel path.

In contrast, in the GTAW (Gas Tungsten Arc Welding) and PAW (Plasma Arc Welding) processes, the arc is formed between a non-consumable electrode, typically made of tungsten, and the substrate. In these processes, the filler material is added into the arc region, where it is melted and deposited as required to form the desired part (Frazier, 2014).

The choice of deposition process for additive manufacturing depends on the complexity of the part and the material being used. Autogenous processes with external wire feeding, despite offering the advantage of independent control between current and material feed, tend to present greater challenges in additive manufacturing due to variability in feeding direction during multidirectional paths, since the feeder is fixed adjacent to the arc. This is not the case in GMAW, where the feeding is coaxial with the arc, making it the most widely used process in wire and arc additive manufacturing today.

One of the main challenges in additive manufacturing is the CAD-to-part relationship, i.e., the integration between computer-aided design (CAD) and the fabrication of the physical component (part). In additive manufacturing, this relationship involves several critical steps. Highlights include process planning and parameterization—welding parameters and operational guidelines that must be programmed into the path, which should ensure that the final part meets the established dimensional and mechanical requirements (Ding et al., 2015a, 2016; Wang et al., 2021). Given this scenario, it is imperative to map and understand the physical phenomena related to metal transfer in the chosen deposition process and its impact on the geometric profile of the deposited beads.

In this context, high-tech welding processes are widely employed in additive manufacturing due to their greater control over metal transfer and welding variables, with the CMT (Cold Metal Transfer) variant of the GMAW process standing out. According to the literature, the CMT system provides geometric control of the deposit, high stability, and allows for high deposition rates—features that are particularly advantageous for manufacturing parts via additive manufacturing (Ali et al., 2019; Furukawa, 2006; Mvola, Kah & Layus, 2018; Posch, Chladil & Chladil, 2017; Yang et al., 2019).

However, even when applying highly reliable equipment and processes, parameterizing an additive manufacturing operation goes beyond the welding process itself, extending to heat input control, interpass or interlayer temperature, path planning and control, among other variables. Neglecting these aspects can render additive manufacturing operations unfeasible (Bai et al., 2018; Ding et al., 2014, 2015a, b, c; Mehnen et al., 2011).

In addition to the fabrication of structural parts and customized components, WAAM also proves to be a viable alternative for applications in sectors such as oil and gas, especially for the production of repair components such as half-shells and clamps, allowing for greater flexibility in manufacturing these structures. Furthermore, this technology can be applied in the fabrication and restoration of critical components, such as valves, flanges, and special fittings, extending the service life of equipment and reducing the need for costly replacements.

In the oil and gas sector, the use of pipelines for transportation is currently one of the most efficient and safest methods. Due to this high level of reliability, such structures are manufactured under strict quality requirements, both mechanical and metallurgical. However, even when using high-grade materials, these structures are subject to defects that may affect their integrity over time. The defect that most compromises the integrity of pipelines is wall thickness loss due to corrosion. In addition, vandalism—such as fuel theft—is another concern. Modifications, such as the insertion of components or expansion of lines, are also common. Given these situations, in-service welding repair techniques are frequently applied, allowing interventions without interrupting fluid flow.

These techniques typically involve welding elements known as half-shells or clamps, which consist of assembling a split housing device with compartments to accommodate leaks and seals, making for a quick—and in some cases permanent—repair.

One of the challenges of these techniques lies in the fabrication of these components, which must meet specific mechanical requirements, often demanding customized parts. In the case of the type B double half-shell technique, it is common to use a section of the pipeline itself, which is adjusted to fit properly within the required specifications. On the other hand, clamps, which are typically contingency solutions but can become permanent in some cases, require the use of high-strength steel alloys, and their manufacturing may involve complex techniques such as casting or forging. Besides the cylindrical structure, accessories such as various types of fittings may be needed.

Moreover, because it is a low-volume commercial product, the costs are high, and logistics are limited. However, companies such as PLIDCO, WESTATLANTIC, among others, offer this solution as an alternative for pipeline repair.

In this regard, as part of a national development initiative, Petrobras, in collaboration with LABSOLDA and GRANTE from the Federal University of Santa Catarina (UFSC), developed a R&D project entitled: “Alternative repair processes: in-service welding of bolted clamps and cap (cover) – SIGITEC: 2017/00379-0.” Within the scope of this clamp project, the focus was on reducing the shell thickness. However, computer simulations indicated the need for additional thickness in critical regions to ensure mechanical integrity. Therefore, this study aims to demonstrate the reinforcement process via additive manufacturing on an industrial clamp used in temporary and permanent repairs of pipelines in the oil and gas sector, presenting the steps of process parameterization, path programming, and hydrostatic testing.

2. Methodology

Clamps for the repair or isolation of leak points consist not only of the shells that form the main structure, but also include a sealing system using O-rings and a cap, as shown in Figure 1. Initially, for the design of the clamp model proposed in this study, a 20” diameter and a dual-sealing system for the cap were defined.

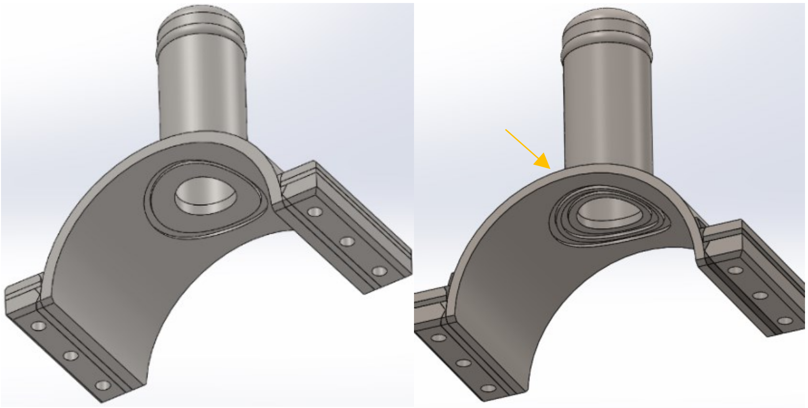

Figure 1 – Clamp with two channels for housing the dual O-ring sealing system.

Subsequently, the shell optimization step was carried out in a virtual environment using numerical simulation, considering the clamp material as API 5L Gr. X65 steel, which has a minimum yield strength of 448 MPa and a minimum tensile strength of 531 MPa. In this simulation, the shell thickness was set at 19 mm (3/4”). Based on the hoop stress equation for thin-walled pressure vessels, it was verified that for an internal pressure of 17.12 MPa, the pipe would reach its yield strength, and for an internal pressure of 20.29 MPa, it would reach its ultimate tensile strength. It is worth noting that according to API 5L: Specification for Line Pipe (2004), the minimum test pressure for this type of pipe is 15.10 MPa (2190 psi).

Following the initial thickness definition test, an optimization was performed aiming to reduce the shell thickness in low-stress regions. The areas defined as non-critical were reduced to 15.88 mm (5/8”), while the critical regions maintained a thickness of approximately 19 mm, preserving the clamp's capacity to withstand a pressure condition of approximately 17 MPa. Within the project scope, two 20” clamps, referred to here as Clamp P1 and Clamp P2, were manufactured for delivery in a relevant environment to CREDUTO (Brazilian emergencial center of pipe repair), with the objective of field application. Prior to their practical application, both clamps were used for project-aligned activities: Clamp P1 was used to conduct an upskilling course for the plant maintenance teams, and Clamp P2 was used for bench testing.

For the clamp fabrication, a 5/8” (15.88 mm) ASTM A516 Gr. 70 plate was used, which has a Specified Minimum Yield Strength (SMYS) of 260 MPa and a Minimum Tensile Strength of 485 MPa. A reinforcement by additive manufacturing (AM) was planned for this component.

The additive manufacturing reinforcement was applied to the regions identified as critical in the numerical simulation step. The reinforced areas included the cap region, in the form of a collar or hyperbolic paraboloid, and the flange attachment area, as shown in the detail of Figure 2.

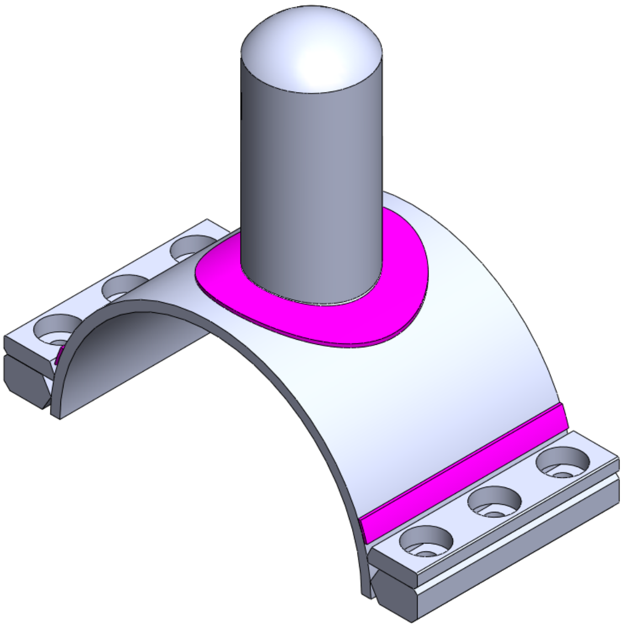

Figure 2 – Isometric view of the clamp CAD model highlighting the regions reinforced by additive manufacturing (AM).

In this specific case, the outputs of the parameter prediction algorithm were directly implemented on the DX100 controller of the Motoman HP20D robot and the MOTOPOS MPD250B positioner, without the use of any CAM software, using the Inform III programming language. This approach was adopted due to the geometric variations between the CAD model and the actual part, which remains one of the major challenges in wire and arc additive manufacturing (WAAM).

Initially, the welding process and its preliminary parameterization were defined. In this case, due to the size of the part, a process with high deposition rate and good bead geometry control was selected. Thus, the chosen process was CMT Pulse, a hybrid variant of the GMAW process with dynamic wire feeding, combining pulsed arc and Cold Metal Transfer (CMT) characteristics. The material used for deposition was a carbon steel wire ER70S-6, 1.2 mm in diameter, along with a gas mixture of 8% CO_2 and 92% argon. The parameters used included a wire feed speed of 6.5 m/min and a travel speed of 60 cm/min, resulting in a bead approximately 7 mm wide and 3 mm high.

For the reinforcement collar, a complex trajectory planning study was required due to the shape of the part. The trajectory programming was performed online, directly on the robot controller, through synchronized motion programming between the robotic arm and the positioner table. The programming was organized into five steps, as shown in the flowchart in Figure 3.

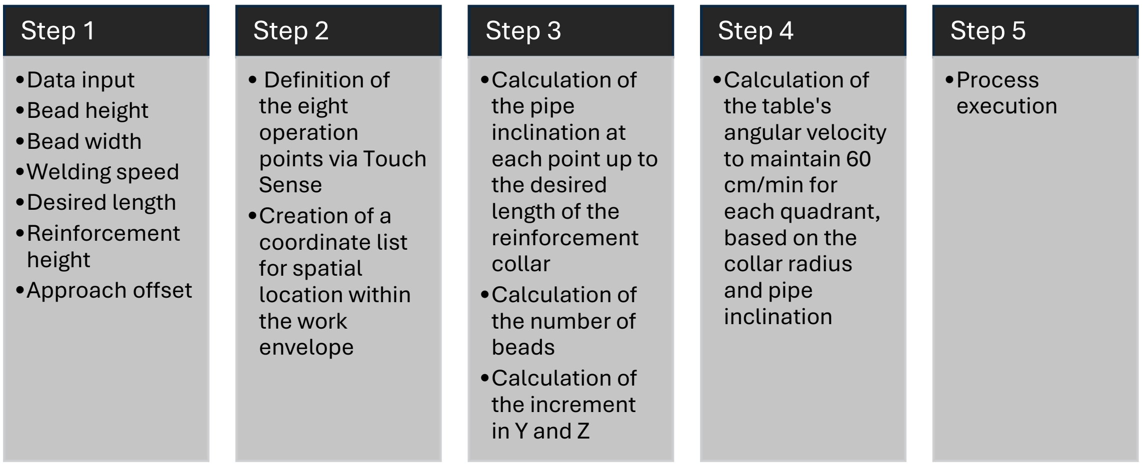

Figure 3 – Flowchart of the trajectory planning used for the reinforcement collar deposition.

For the flange reinforcement, a linear bead trajectory was used, with alternating beads overlapped at a center-to-center distance equivalent to 67% of the bead width, or 4.2 mm. Additionally, using the MOTOPOS positioner, the clamp was tilted to position the flange reinforcement operation in the flat position.

For validation and inspection of the clamp, visual inspection, penetrant testing, measurements, and finally a hydrostatic test were performed to validate the prototype. It is worth noting that four identical clamps were built for testing and validation of the created model. For the hydrostatic tests, a test bench was set up with a 20” external diameter balloon made of API 5L steel, and an automated hydraulic pump made of AISI 316L, with a maximum pressure capacity of 300 Kgf/cm^2, as shown in Figures 4a and 4b.

Figure 4 – a) Balloon for testing; b) Hydrostatic pump.

A hydrostatic test was performed on each of the clamps, and the main criterion used was resistance to pressure of at least 155 Kgf/cm², equivalent to 1.5 times the operating pressure, which is the target value for the qualification of repairs for class #600. In addition to this criterion, as per the design specifications for the clamps, a torque of 600 Nm was defined for tightening each bolt.

3. Results and Discussion

As described in the methodology, the reinforcement by AM was performed in critical regions, including the area near the capote and the flange area. Although the project initially aimed at reducing thickness to decrease mass, the expected loads in these regions required localized reinforcement to compensate for the thickness reduction in these areas. This was done while maintaining the premise of structural optimization and mechanical strength.

For better understanding of the process, the following Figure 4 contains QR codes linking to demonstration videos of the touch-sense operations, the reinforcement collar fabrication, and the reinforcement of the flange.

Touch-sense | Reinforcement of the Collar | Reinforcement of the Flange

Figure 4 – QR-Codes for examples of the main operations performed in the additive manufacturing reinforcement process of the clamp.

The result of the reinforcement applied to the clamp can be seen in Figure 5. Figure 5A illustrates the deposition stage of the collar around the capote, while Figure 5B presents the deposition stage of the reinforcement on the flange. It is important to note that the reinforcement of the flange was carried out on both sides of the clamp.

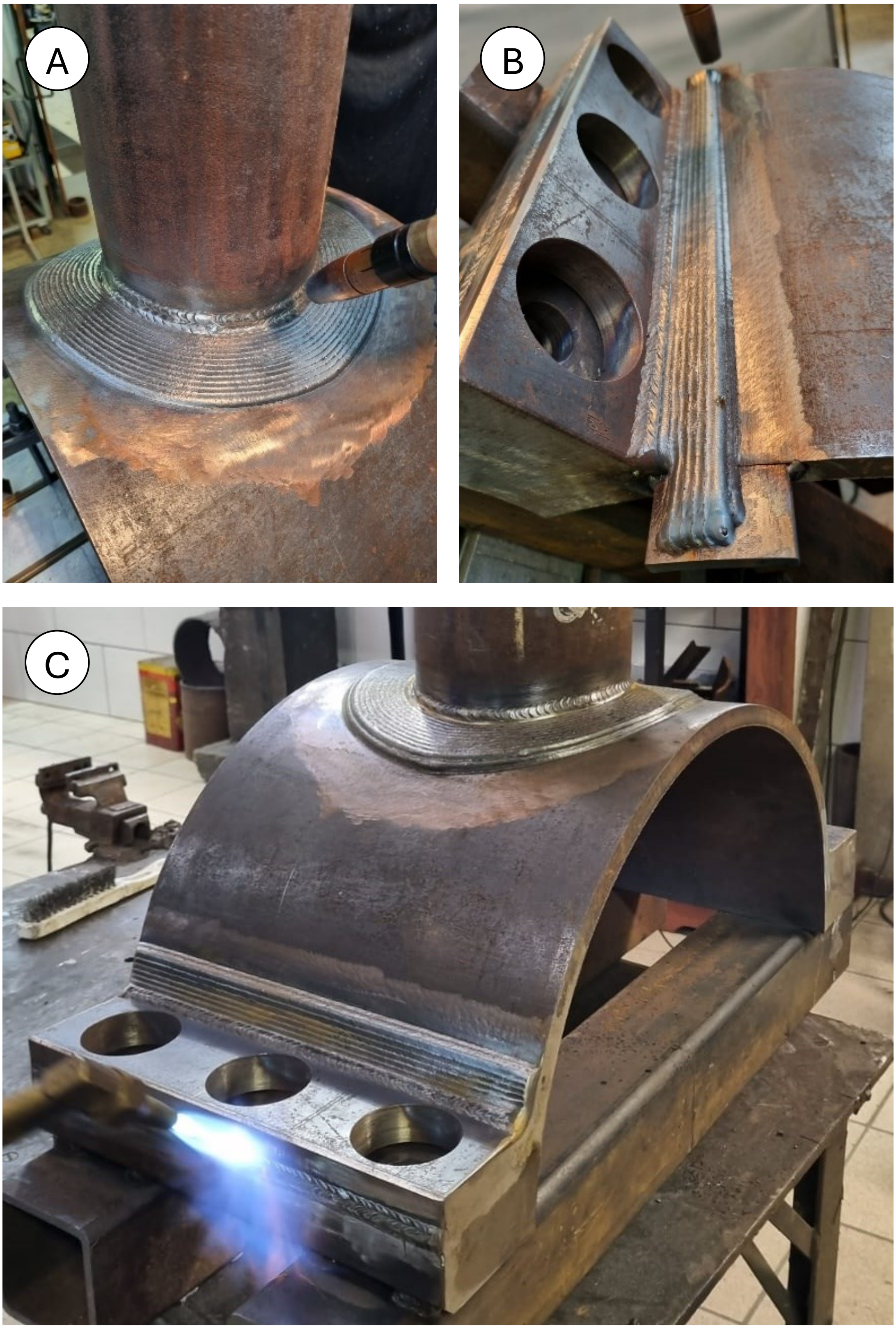

Figure 5 – Result of the additive manufacturing reinforcement process on a clamp for oil and gas pipeline repair.

The measurements performed on the clamp focused on the diameter of the flat section, width, and thickness of the reinforcements. The results of these measurements are detailed in Table 1. It was found that all measurements were within the initially defined tolerances, with a low standard deviation.

Table 1 – Measurement of the clamp reinforcement.

Feature	Section A			Section B		
	Nominal (mm)	Mean (mm)	Std. Dev. (mm)	Nominal (mm)	Mean (mm)	Std. Dev. (mm)
Diameter / Width	278 ± 3	280.3	0.4	32	32.3	0.4
Thicknesses	Min 5	6.4	0.3	Min 5	6.3	0.3

The clamp was tested in the same test balloon previously mentioned, with a diameter of 511.99 mm, using rubber seals with a cross-sectional height of 14 mm and thickness of 15 mm, and a torque of 600 N/m/bolt. The clamp withstood a pressure of 160 Kgf/cm². Additionally, this clamp exhibited a final gap between the flanges of approximately 10 mm with a variation of +1 and -1 mm.

Regarding the first experiment conducted with this clamp at CREDUTO, as shown in Figure 6a, Viton sealing gaskets with a shore hardness of 60, a height of 10 mm, and a width of 15 mm were used. The bolts were tightened in the required sequence, progressing from 200 Nm up to 600 Nm per bolt. The gap measured between the flanges was around 3 mm with a tolerance of -1 and +1 mm, as shown in Figure 6b. The hydrostatic test was conducted, and the pressure achieved was 160 Kgf/cm², as shown in Figure 6c, a value sufficient for the validation of class #600 repairs.

Figure 6 – a) Installed clamp; b) Recording of the flange gap; c) Recording of the achieved pressure.

This same clamp was tested for the second time at CREDUTO, under a condition that differed from the first only in the torque applied to the bolts, which was 400 Nm per bolt. The result of this second test showed that, even with a lower torque, the sealing rubber withstood a pressure of 160 Kgf/cm2.

4. Conclusion

The offline programming method adopted, using the touch-sense feature and velocity calculations based on the sample's tilt, proved effective for achieving the goal of constructing a collar around the capote through additive manufacturing. Furthermore, the welding process adopted demonstrated high stability in terms of both process and geometry, producing a defect-free weld with low standard deviation.

The clamps produced are the first prototypes tested at CREDUTO, featuring two sealing channels and the application of a reinforcement collar via additive manufacturing. Additionally, the use of sealing rings with a prismatic cross-section proved more efficient in the tests conducted. However, it is important to emphasize the need to follow the installation instructions for the clamp.

In conclusion, the team involved in the test noted the ease of clamp installation due to its lighter weight compared to commercial clamps, a significant improvement that has been mentioned in other reports.

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