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## Abstract

The oil and gas sector have great importance in Brazilian economy due to the high demand of the country's energy matrix. The most advantageous alternative for the flow of oil-derived fluids is the use of pipelines. However, one of the main challenges for the construction of these flow lines is the way that the pipes produced by special materials are joined. Currently, in the Brazilian scenario the execution of the welding process, for stainless steel and nickel-based alloys consists mostly of manual applications, becoming hard the increase in welded joints productivity and repeatability. Therefore, the automation of this step allows several advances such as more reliable results, lower costs and healthier condition for welders. Therefore, experimental tests were carried out in a 304L stainless steel pipe laid out at 5G position. The samples were welded by GTAW with dynamic wire feeding process, using a robotic manipulator in two steps of 180° in vertical down progression. The welding parameters obtained are discussed and the puddle behavior during the root pass was online monitored by videography. It was possible to reach high welding speeds in the root pass, around 50 cm/min in a *keyhole* mode. The wire's movement contributed to reach great process stability and robustness, for all joint filling passes. The macrographs and x-ray analysis did not indicate discontinuities as porosity and lack of fusion.

**Keywords:** Spools welding; TIP TIG; stainless steel pipe welding; Root pass.

## 1. Introduction

The pipeline welding process is one of the main manufacturing steps for the oil and gas industry, whether in joining, coating or repair applications. In this context, the Gas Tungsten Arc Welding (GTAW) process is preferred under conditions in which quality requirements must be prioritized. However, due to the challenges in terms of reliability and robustness, the automation of the welding process is difficult to be implemented in real applications, with most operations still occurring manually. Thus, many works have been developed aiming the increase in stability, robustness and automating level for GTAW process, maintaining the quality characteristics by which the process is recognized. Richardson [1] and Ouyang et al. [2]

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provided examples which show the implementation of the automatic wire feeder in GTAW welding, in these cases the welder just controls the welding torch and the melted puddle. Nowadays, this tool is widely used in numerous commercial equipment.

Similarly, Hori et al. [3] in order to increase the melting rate of the welding metal, presented a version of the GTAW with automatic feeding called pulsed hot wire, in which a preheating is applied to the wire through the passage of a pulsed electric current. Compared to conventional process, the hot wire technique also provides an increase in the welding speed, as presented by Anantha et al. [4].

Over recent years, a new approach of wire feeder has been used in which a forward and backward movement is applied to the feeder by an electromechanical system. This creates a similar behavior in welding wire's tip, increasing the process robustness and smoother metallic transfer [5]. Silva et al. [6] called this technique as dynamic wire feed. The authors show that during the forward and backward cycles, the wire undergoes intense accelerations and decelerations and reaches instantaneous speed higher than the average value, different from the traditional technique in which the wire is fed in a constant mode in a quasi-static regime. According to Riffel [7], the higher speed during the forward allows the wire to run through the electric arc isotherms at high speed, and prevents the formation of droplets in its tip, which generates a higher robustness for out of position welding. The same technique was applied by Silva et al. [8] in a frequency of 1.25 Hz, the objective was joining high-strength steel pipes for the oil and gas industry, the author also showed the possibility of increasing productivity in root pass welding for an automated welding. Silwal and Santangelo [9] using frequencies around 16 Hz, reported a vibration in the filler metal that provided an extra force assisting in the transfer of the wire to the puddle. In this case the authors used a drop transfer without the constant contact of the wire with the weld puddle as Cheng et al [10] characterized in their study. However, the authors restricted the experiments in bead on plate depositions, without evaluating the influence of the vibration in more critical situations, as an orbital welding for example.

The keyhole mode is recognized in the welding field as a high performance condition, which enables deeper penetration profiles, higher productivity through less joint machining and faster welding passes, compared to conventional mode [11]. Generally, the processes linked to keyhole mode are the LASER Beam Welding, Electron Beam Welding and the PAW (Plasma Arc Welding). In the case of arc welding processes, for PAW the main justifications are based on the greater arc constriction, plasma mechanic action and greater current density, which promotes a more localized pressure over the base material, provided by the recoil and stagnation pressure [12]. Jarvis and Ahmed [13] presented the possibility of reach the keyhole mode with the GTAW process either, under different mechanisms of keyhole formation compared to those for LASER and PAW. In this case, the author identified the electromagnetic force (Lorentz force) as the main responsible for the cavity formation, which must be capable to overcome the metalostatic pressure (inner pressure in a liquid due to gravity force) and the molten material's surface tension. Currents from 300 A are cited in the literature as capable to reach the keyhole mode, depending on the base material's physical properties and dimensions, in addition to the electrode sharpening angle. This last one changes the arc constriction and can generates significant differences in the plasma velocity.

Indeed, there is a great complexity in keyhole parametrization. The necessity of high current levels indicates the tendency of humping defects due to high arc pressure over the molten puddle. Thus, the input of filler material is necessary to mitigate problems related to humping, compensate gaps in the joint and undercuts prevention. Jarvis and Ahmed [13] used the filler wire inserted through the arc's fusion front, but this position promotes an extra barrier under the arc, formed of molten material, that avoids the arc action directly over the base material. The wire insertion from behind the arc (solidification front) can facilitate a more efficient fusion of the base material, as well as the keyhole's closing.

Jarvis and Ahmed [13] cited the necessity of gas mixtures with Ar+H<sub>2</sub> and Ar+N<sub>2</sub> to reach a stable keyhole, although Olivares [15] showed suitable results using just pure Argon in 8 mm thick carbon steel plates. However, the keyhole application out of flat position is overly complex, because the interference of external forces as the gravity. Techniques to overcome the difficulties in the out of position keyhole application are presented as solutions. Li et al [16] shown a PAW special technique called Double Stage, which has a specific wave format in pulsed current aiming to stabilize the keyhole crater out of the flat position. Therefore, commonly the keyhole is presented for pipes welding in a stationary way, in which the torch is kept static in flat position, and the pipe rotates around its own axis [11]. In automated orbital welding, executed at 5G position, the pipe remains static while a weld head conducts the welding torch along the circumference. In this case, the main problem faced in arc welding process is the change of the puddle behavior at different positions. At flat position the gravity force acts in the same direction as the electromagnetic force, facilitating the weld penetration. For the vertical position, there are two different behaviors that can occur, depending on progression of the welding torch, vertical up or vertical down. In the vertical up the puddle tends to flow in the opposite direction in relation to torch movement, creating an optimal condition to increase the penetration, but a prejudicial situation to close the keyhole, for example. In other way, the vertical down creates a condition in which the gravity force produces a counter flow in relation to welding torch movement. This fact creates a barrier under the arc, which becomes a conductive condition to lower penetration. In the overhead position, the gravity force vector acts counter to the electromagnetic force vector, with a tendency to form a weld bead more convex in its face and concave at the root reinforcement.

Kou [19] presented a description of the main forces acting over the puddle, as well as them vector direction with the positions change in an orbital welding. The author branches the main forces into: gravity force; electromagnetic force; surface tension force; and drag force of the plasma jet. The behavior of the molten material is therefore dependent on the chemical composition of the weld metal. Then, stainless steels and nickel alloys are known to have low wettability when compared to conventional steels. This is due to the presence of alloying elements, such as Cr and Mo that have higher surface tension coefficient in melted state. Therefore, the behavior of the welding puddle may be strongly influenced by the surface tension force. In addition to the behavior of the puddle, the metal transfer must be kept constant and stable throughout the whole pipes' circumference, avoiding contamination of the electrode and consequent interruption of the process. In this way, the conjunction between keyhole mode and dynamic wire feeding maintains a stable metallic transfer and yields productivity benefits in the root pass for pipes/tubes orbital welding.

This work aims to develop an automated orbital welding methodology for stainless steel pipes, which are materials recognized for their difficult weldability. The methodology was based on the application of the GTAW keyhole process with dynamic wire feeding technique in the root pass, with higher travel speed, and GTAW with dynamic feeding for the filling passes. The phenomena and the behavior of GTAW puddle during the keyhole welding of the root pass were identified through online HDR videography, as well as macrographs and X-ray tests for joint validation were highlighted and discussed.

## **2. Materials and Method**

An AISI 304L stainless steel pipe with 1/2" (12,7 mm) thick and 12" (304,8 mm) of diameter was used as base material. As filler wire it was applied the AWS 309LSi 1,2 mm of diameter and pure Argon used as shielding and purging gas, to protect the weld seam. The cathode was a Tungsten electrode with 3,2 mm of diameter doped with 2% Cerium and

sharpened with 40°, the Table 1 shows the common parameters for all welding passes. The joint design was a “U” profile as the dimensions shown in Figure 1. The orbital welding process used was the GTAW with dynamic wire feeding, which means a forward and backward movement applied in the wire feeder, as shown previously by Silva et al. [5]. In this case the wire’s oscillation frequency was around 20 Hz and the hot wire technique was also used. The wire was inserted from behind to the arc. The welding steps by each layer (root and filling passes) consisted of two weld beads, starting at 12 o’clock position and finishing at 6 o’clock (carried out in 180° of the pipe to complete the 360°). The root pass welding was online monitored by a camera model HEMA ICAM Weld, which was fixed on the torch’s body, enabling puddle imaging along the entire circumference. The vertical down progression was adopted for better keyhole stabilization. Three samples were welded for replication. Finally, macrographic analyzes and x-ray tests, according to ASME Section- IX requirements, were performed on the welded joints. The welded pipe was cut in 8 equal parts (at each 45°) to enable the x-ray test and the equipment used was a model ERESO 65 MF4 Control, and the parameters were a voltage of 180 kV, current of 3 mA and exposure time of 54 s.

Table 1. Parameters for all welding passes.

Parameter	Value
Gas Flow Rate (lpm)	12
Filler Wire Oscillation Frequency (Hz)	20
Dist. Between Electrode/wire (mm)	5
Dist. Between Electrode/work piece (mm)	3
Angle between Wire/Electrode (°)	45

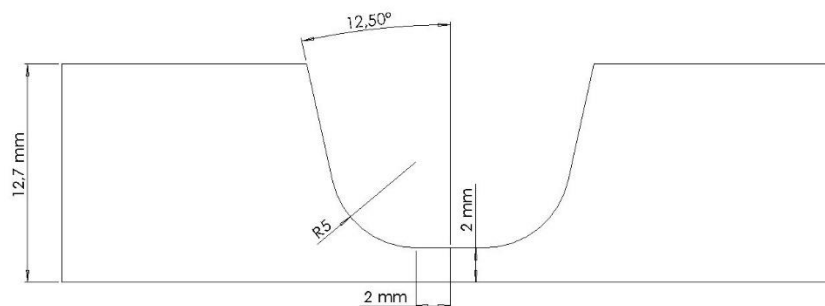


Figure 1. Joint Configuration, groove design.

### 3. Results and discussion

#### 3.1 Root pass

To carry out the root pass, the main challenge was to deal with the variation of the puddle due to the variation of the welding position and forces acting over the process. These variations in the puddle aspect were more critical on the root pass due to the necessity to keep the keyhole steadiness and avoid weld bead geometric changes, which can strongly affect the joint penetration with defects, as burn through or lack of fusion, and consequently a repair or the filling passes execution. The keyhole geometry and stability were only overcome by the welding parameters variation through the circumference. The parameters reached for each sector of the pipe, which was welded into two parts of 180°, are shown in Table 2.

Table 2. Root pass parameters.

Root pass					
Sector range		Current		Wire speed	Travel speed
1	0° - 20°	290 A		1,80 m/min	50 cm/min
2	20° - 160°	370 A		1,50 m/min	50 cm/min
3	160° - 180°	300 A		1,65 m/min	50 cm/min
Torch weaving					
Amplitude	2 mm	Frequency	2 Hz	Stopped time	0 s

With the parameter variation a stable condition was obtained in keyhole mode. Although the recognized difficult to stability it in the out of position welding, it was possible to reach process robustness just with constant current, albeit the welding position changes must be accurately identified. Assisted by the online videography, a strong change in the behavior of the puddle (keyhole) was observed at the angles of 20° and 160°. These points were defined as the transition between the flat to vertical down position and the vertical down to overhead position, respectively. At 20° position the keyhole tends to close quickly and the penetration becomes insufficient, creating lack of fusion points. On the other hand, at 160° the keyhole enlarges strongly and the welding current must be reduced to avoid the burn through. Table 2 shows that the welding current is lower in the range of 0° to 20° (flat position) in which the penetration is assisted by the gravity force, together with the electromagnetic force. Then, once the 20° position is achieved, the puddle begins to flow under the arc creating a barrier that hinders the keyhole maintenance, which tends to close quickly and the penetration becomes insufficient, creating lack of fusion point. Thus, there is a need to increase the intensity of the welding current, and consequently the arc's pressure over the puddle. The filler wire's speed is also reduced, so the amount of arc's heat transferred to the wire is also lower and more heat is directed to melts the base metal. The dynamic wire feeding and its vibration over the puddle can mitigate the defects generation, according to metallic transfer behavior discussed in other works [5-7]. In the overhead position (from 160° to 180°) the behavior of the puddle changes again, in this case was necessary to reduce the intensity of the welding current in order to avoid burn through, which would occur if it was kept at the same intensity as the vertical position. Although the gravity force vector acts contrary to penetration, the overhead position had a similar behavior to the flat position with very similar current intensity and wire speed parameters, although the wire speed has been slightly reduced to avoid excessive convexity on the face of the weld bead, identified in preliminary tests.

The entire aspect of the face and the inner root pass reinforcement are shown in Figure 3. There was an excellent wetting on the face of the weld bead, with no significant geometric difference along the pipe's circumference, as well as full penetration at all points. Even with the change in the parameters, the geometric aspect was kept similar, due to the change in the forces acting over the weld puddle. It is also emphasized that was reached a slightly concave geometry on the root pass' face, satisfactory in preventing defects such as lack of fusion, in the deposit of the first filling pass. It is clear that special conditions and constraints must be developed and set in order to achieve a stable keyhole out of position.

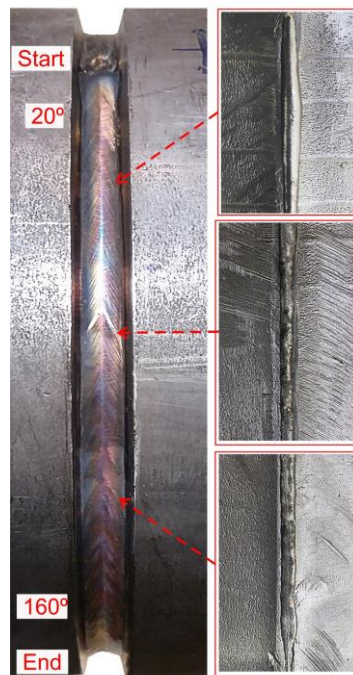


Figure 3. Surface and internal aspect of the root pass.

The online root pass videography which detach the cavity profile is shown by frames in Figure 4. The insertion of the wire from behind the arc facilitated to reaches the keyhole condition, as it provides a direct attack from arc's fusion front to the base metal (indicated by the arrows in Figure 4). During the flat position (Figure 4a) a larger hole is verified when compared to the 20° position (Figure 4b), where the hole tends to close and therefore the current is intensified to maintain the constant full penetration. During the vertical position (Figure 4c and Figure 4d) the keyhole is maintained. At 160° (Figure 4e) the current intensity is reduced and the hole maintains its size up to the 180° position, in which it is closed with the application of a down slope in the current intensity until the arc off.

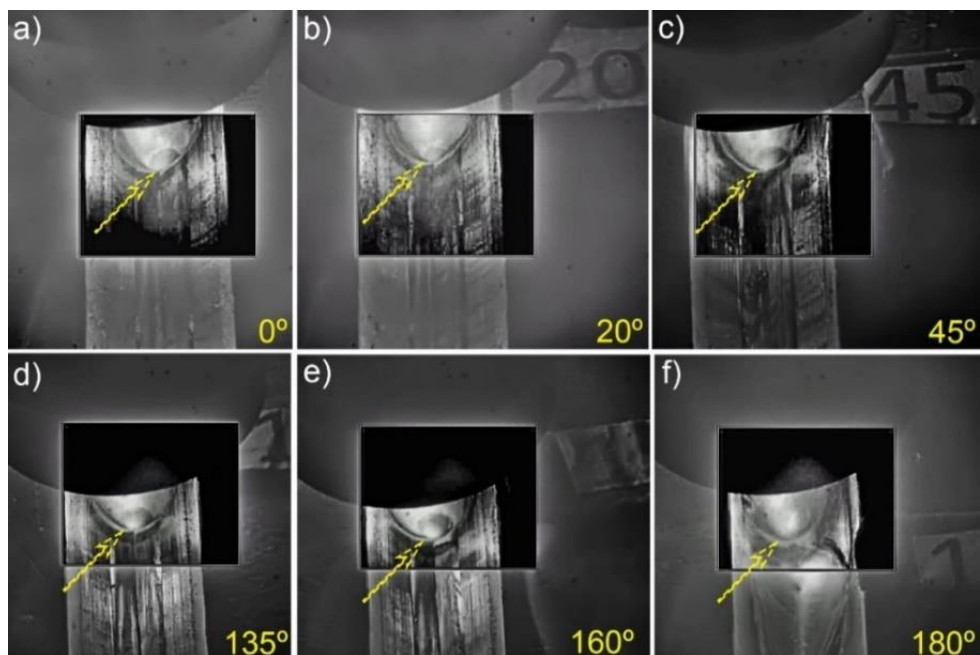


Figure 4. Keyhole aspect during the root pass along the pipe's circumference.

The frontal videography of the keyhole profile hides the filler wire melting in the puddle, so an efficient way to verify its regularity is by the welding voltage signal. Silva et al. [5] showed that the dynamic feeding promotes an oscillation in the voltage signal due to the wire's movement under the arc. Each peak oscillation in the voltage corresponds to a forward and backward event. Despite this, as detailed in the literature, it is possible to reach conditions in which the metallic transfer is through bridge mode (wire in constant contact with the puddle), depending on conduit layout, the forward and backward movement is not transferred to the wire's tip [5-7].

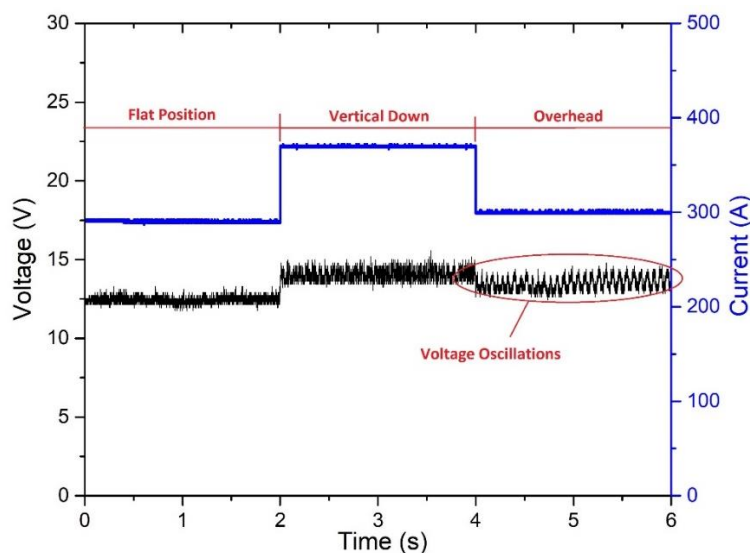


Figure 5. Current and voltage signals during the root pass along the pipe's circumference.

### 3.2 Filling and finishing passes

The joint filling was divided into four filling passes and one finishing pass. The welding parameters for filling passes are shown in Table 3 and the parameters for finishing pass are shown in Table 4.

Table 3. Welding parameters for the four filing passes.

Filling passes					
Sector range		Current		Wire speed	Travel speed
1	0° - 20°	250 A		1,80 m/min	13 cm/min
2	20° - 160°	250 A		1,80 m/min	13 cm/min
3	160° - 180°	250 A		1,80 m/min	13 cm/min
Torch weaving					
Amplitude	5 mm	Frequency	0,4 Hz	Stop time	0,5 s

Table 4. Welding parameters for the finishing pass.

Finishing pass					
Sector range		Current		Wire speed	Travel speed
1	0° - 20°	200 A		0,85 m/min	9 cm/min
2	20° - 160°	200 A		0,85 m/min	9 cm/min



3	160° - 180°	200 A	0,85 m/min	9 cm/min	
<b>Torch weaving</b>					
Amplitude	14 mm	Frequency	0,6 Hz	Stop time	0,8 s

In theory, the realization of the filling passes has lower difficulty when compared to the root pass. However, alloying elements such as chromium, present in the base material (304L) and in the filler metal (309LSi), besides molybdenum present only in the wire, provide less wettability to the puddle, creating a situation favorable to defects, as lack of fusion on the groove's side and between passes. Both filling and finishing passes, carried out on lower speed when compared to the root pass, the welding current had no changes in its value along the pipe's circumference. For the filling passes it was obtained a good weld bead spreading, applying 5 mm in the torch's oscillation amplitude. It is important to verify that the "U" groove profile has a smaller volume when compared to other equivalent geometries, as the "V" one, if applied on the same conditions. Therefore, this profile, known as narrow gap, aims to increase productivity by reducing the amount of material needed to fill the joint, although it is a profile that limits the lateral torch movements. In the final finishing pass, an increase in the torch's oscillation amplitude was allowed, which was increased to 14 mm, since the electrode is no longer inside the groove, resulting in a condition similar to a deposition over the pipe surface. This greater amplitude allowed a larger weld bead spreading, generating an excellent superficial aspect. It is important to note that the purge gas was maintained during the entire joint welding, because the high temperature reached inside the pipe, until the end of the finishing pass in conjunction to the presence of oxygen, generates the formation of oxides that reduce strongly the weld mechanical resistance and corrosion resistance. Figure 6 shows the aspect of all filling passes until the finalization of the joint.



Figure 6. Superficial aspects of filling passes e finishing pass.

The filled joint macrographs correlated with its circumference position are shown in Figure 7. No macroscopic discontinuities were found and the penetration was satisfactory.



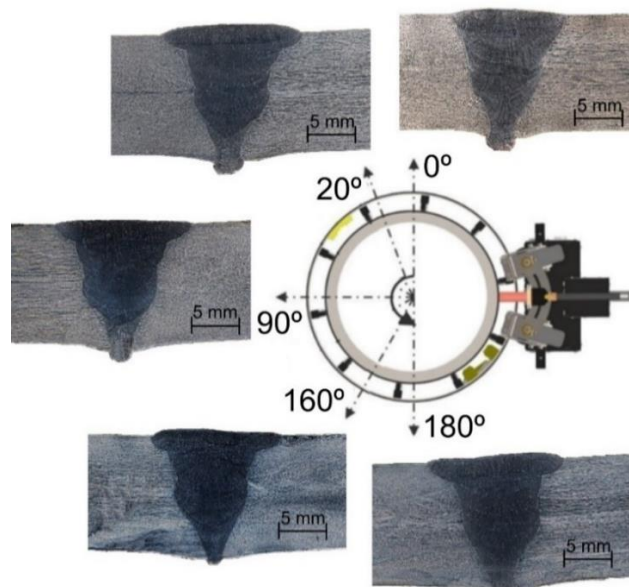


Figure 7. Macrographs of the complete joint in different joint positions.

#### 4. Conclusions

The importance in the joining of stainless steel pipes is recognized in the oil and gas industry. Therefore, this work fills an important gap in the search for the automation in the circumferential welding steps pipes, showing that it is possible to combine both characteristics: productivity and quality in the spool fabrication process.

The keyhole technique was successfully joined with the dynamic wire feeding technique, providing a method and procedure for obtaining defect free, full penetration root and fill passes, as proven by macrographic and x-ray tests. Another positive and distinguishing aspect attained in the root pass was the high travel speed reached, of about 50 cm/min.

The dynamic wire feeding assisted all welding steps, from the root to the finishing pass. Although providing stability over the entire weld, its distinguishing effect is highlighted in the overhead position, where an otherwise constant speed wire feed would tend to result in electrode contamination by large wire droplets formed on the wire's tip. The forward and backward wire movement results in a robust, repeatable and reliable small droplet transfer, mitigating process instabilities.

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