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ORIGINAL ARTICLE

On Orbital GTA Root-Pass Welding: Evaluation of AVC Performance, Bevel Geometry Influence and Wire Feed Technique

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Abstract: Welding operations are one of the most important operations during pipeline construction and most are still carried out manually with SMAW. The challenges associated with the automation of orbital welding are related to several variables, including the weld pool behavior in vertical and overhead positions, monitoring of parameters and metal transfer, bevel preparation and orbital welding head control. In order to achieve a 360º orbital root pass with GTAW process, this study was focused on evaluating the influence of the arc voltage control (AVC) system for pulsed current process, the bevel geometry and filler wire insertion technique on the welding process and weld bead. Experiments were carried out using 16" ASTM A36 pipes with ½" wall thickness and an automated orbital welding head. The results show that the AVC control must be appropriate for the current mode applied (pulsed or constant) in order to avoid arc length oscillation. Also, the counterboring operation during the bevel preparation increases the amount of material of the groove land and promotes less penetration. Regarding the metal transfer, the continuous bridge transfer mode is recommended for automated orbital GTAW welding and this is achieved with an appropriate AVC control method and filler wire positioning.

Key-words: GTAW; Orbital welding; Roots pass; AVC; Bevel geometry.

1. Introduction

In the oil & gas industry, welding operations are one of the most important phases during the repairing, assembling and maintenance of pipelines. In recent years, the Brazilian pipeline network has increased as the number of proven reserves of oil and natural gas has risen [1]. However, mechanized or automated orbital welding procedures are still challenging and most of them are carried out manually by SMAW process. In this context, research and equipment's development are underway worldwide, in order to achieve better quality and productivity for girth welding procedures.

According to Baek et al. [2], for manual stick welding the bevel angle of pipe-to-pipe joints generally needs to be 60º, in order to enable the welder to perform the procedure with sufficient accessibility. The use of smaller groove angles reduces the amount of material to be deposited and increases the productivity, but this can lead to the presence of discontinuities, such as lack of fusion or incomplete penetration (root pass). Thus, as mentioned by Kim et al. [3], different groove geometries are designed and tailored for each welding condition. Also, Baek et al. [2] claims that the use of smaller bevel angles promotes up to 50% less welding passes than a manual procedure. Smaller joints can be achieved by reducing the gap (root opening) between the pipes or even completely removing it. This is recommended for automated GTAW procedures since it avoids arc burn through and that solid wire is fed though the gap, besides promoting a better support of the molten pool. Furthermore, in pipe production, tolerances over the pipe circumference may lead to variations in the root face thickness during the bevel preparation. To ensure a uniform face thickness over the whole joint, machining tools manufacturers recommend a counterboring operation (inside diameter machining). To achieve acceptable repeatability, better welding quality and less discontinuities in automated orbital welding, the bevel must be prepared uniformly along the pipe, ensuring the same geometry throughout the joint.

In pipeline construction the tube is fixed and a girth welding procedure is needed. In automated procedures, a robot manipulator moves the arc around the piece, similarly to an orbit, and, according to Silva et al. [4], the molten pool behaves distinctly in each position. Silva et al. [5] also elucidates that the greatest challenge in orbital welding concerns in keeping the molten pool stable in the different welding positions and, to achieve this, it is common to vary the welding parameters for each position. As described by Shirali and Mills [6], in the flat position the gravitational and electromagnetic forces act in a way that

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benefits the weld pool penetration. In the vertical position with a downward progression the molten pool flows in the same direction of the welding . Thus, the coupling of the molten material and the arc reduces the direct contact with the base metal, causing less penetration. On the other hand, on vertical upward progression the weld pool flows in the opposite direction to the welding, and the thin layer of molten material below the arc favors the weld bead penetration due to the direct coupling with the base metal. In the overhead position, in contrast to the flat position, gravitational forces act against the penetration. In this context, not only the bevel geometry needs to be considered and monitored to obtain better results. Because of the molten pool behavior, other variables must also be evaluated, such as the arc voltage control (AVC) parameters and metal transfer modes.

Concerning the metal transfer, in conventional wire feeding in GTAW processes, different operative modes exist, in dependence of welding electric parameters and wire feeding parameters. Authors have given several different names to the metal transfer modes. According to Yudodibroto et al. [7], in cold wire GTAW, it is possible to achieve four different situations: intermittent wire melting; uninterrupted bridging transfer; interrupted bridge transfer; and free flight transfer. The first mode is characterized by inappropriate positioning and low wire feed speed. In the second mode, the wire touches the weld pool edge and the contact remains smooth and uninterrupted. In the third mode, the "bridge" contact between the wire and weld pool is broken periodically in a controlled and well-defined way. The last transfer mode, which should be avoided, represents a situation where the wire feed speed is too low and the tip of the wire melts before touching the weld pool, forming a coarse droplet that detaches from the wire due to gravity and the surface tension. In this case, electrode contamination is imminent. Fortain et al. [8] refers to the interrupted bridge transfer as "droplet transfer" while Chen et al. [9] calls it "touching transfer". Figueirôa et al. [10] refers to the metal transfer modes as non-continuous and continuous transfer. Thus, the terminology for the metal transfer modes in the GTAW process is still not consolidated worldwide. Herein, the following terms will be adopted: "continuous bridge transfer" for the continuous contact between wire and weld pool and "intermittent bridge transfer" for the interrupted bridge transfer mode.

Besides the welding parameters, the metal transfer mode also affects the behavior of the arc voltage signal. In the GTAW process, as described by Wang et al. [11], there is a consistent and well defined relationship between the arc voltage and arc length, which can be monitored and controlled through an AVC (Automatic Voltage Control) system, through the acquisition of the voltage signals. The use of the arc signals as a sensor is an advantageous method due to the simplicity of acquisition, stability and robustness, and, as mentioned by Zhang et al. [12], this approach also offers a closer relationship with the physics phenomena of the welding processes. However, for pulsed welding currents, different voltage values are expected for each welding current level. According to Koseeyaporn et al. [13], for AVC systems based on just one reference voltage, as the arc voltage-to-arc length relationship is not constant, the arc length will not be maintained constant in pulsed current processes, hence definitely disturbing the operation. In automated processes, a proper AVC system is an indispensable tool to provide reliability and repeatability of the welding procedures, all the more so for orbital welding heads.

This work aimed at investigating and evaluating the influence of the three mentioned variables (bevel geometry, AVC control and metal transfer) over process stability and overall performance and, subsequently, developing suitable technique (customized setup and parameterization of AVC, welding arc and wire feeding) for an automated 360º orbital root pass with GTAW process.

2. Materials and Methods

The procedures were carried out on ASTM A36 low carbon steel plates of ¼" (6.35 mm) thickness, and pipe sections of 100 mm length with a diameter of 16" (406.4 mm) and wall thickness of 1/2" (12.7 mm). The sections were coupled to a longer pipe section in which the orbital welding head was mounted. For the filler material an AWS ER70S-6 wire with 1 mm in diameter was used. Pure argon (99.99%) was adopted as the shielding gas. The power source used was a multiple process power source with nominal power of 10 kVA and max. current of 400A (280 A - 100%), and the torch was an automatic GTAW torch with max. current capacity up to 400 A, water cooled, with an EWCe-2 tungsten electrode of 3.2 mm in diameter. The sharpening angle of the electrode tip was 30°. The torch was also equipped with a wire guide for the consistent insertion of the filler wire in the molten pool. The electric signals (voltage and current) and wire feed speed were acquired in a sampling rate of 5 kHz. The orbital welding head used allows the torch to travel along four different axes. The welding head also has an AVC system, for the online control of the voltage/arc length.

The experiments were assisted by photo and video images obtained with digital SLR camera equipped with a 180 mm f/3. 5 macro lens and 671±4 nm bandpass filter. The macro geometry was measured via software and the values exposed are average values of three measurements. This methodology was carried since there was one macro for each condition analyzed.

Figure 1 shows the schematic setup of the testing bench used during the orbital experiments.

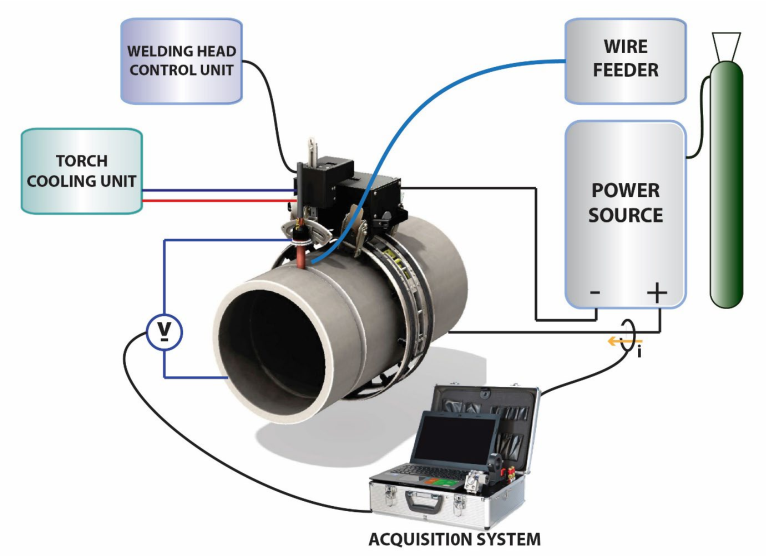

Figure 1. Schematic diagram of the testing bench.

For the AVC optimization and evaluation of the wire feeding technique, the experiments were carried out over steel plates. For the orbital welding experiments, base parameters were set in preliminary tests on beveled joints at flat position in order to achieve a full penetration root pass in accordance to the API 1104 standard 20th Ed. Section 9 and DNV-OD-F101 Offshore Standard (2012). The base parameters used are listed in Table 1.

Table 1. Preliminary test welding parameters.

Parameter	Unit	Value
Welding current (pulse / background)	A	180A / 110A
Pulse and background periods	s	0.4 / 0.4
Wire feed speed (pulse/background)	m/min	1.2 / 0.7
Travel speed	mm/s	1.7
AVC voltage (pulse / background)	V	10.0 / 8.4
Wire feed angle range	Degrees (°)	50-60
Shielding gas flow	l/min	12

Considering the boundary conditions given, the experiment was carried out on J beveled pipes (Figure 2b) to evaluate the process during a 360° root pass procedure. The J bevel was selected because of its lower opening angle (12.5°), and the round corner (R5), which would prevent lack of fusion on the groove walls. The welding procedures were executed in the counterclockwise direction and the pipeline section was split into twelve segments as shown in Figure 2a.

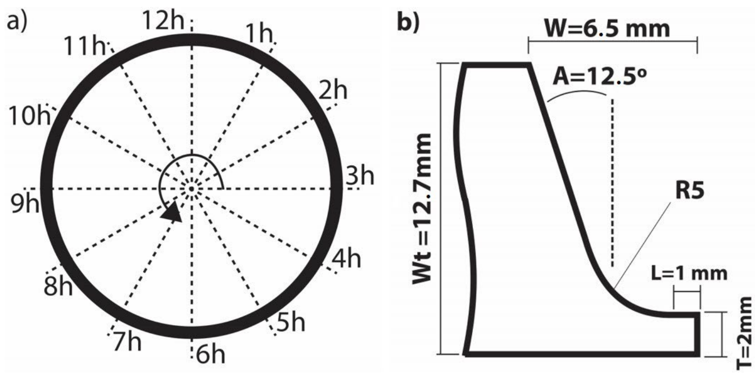

Figure 2. Schematic diagrams of (a) 360° sections of the pipeline and (b) J bevel geometry: W = Half Opening; L = Land; T = Face Thickness; Wt = Wall Thickness; A = Bevel Angle.

3. Results and Discussion

3.1. On the arc voltage control (AVC)

To achieve the 360° orbital root pass, the need of an enhanced arc voltage control for pulsed current was detected, since the arc voltage would vary for each current phase. For constant current process, the AVC reference voltage is set according to the desired arc current and arc length. For pulsed process, the operation of the AVC based on only one reference voltage will lead to a variation in the arc length during the process. According to Figure 3a, for the same reference voltage, the arc length is different for the pulse and background periods. In this case, the AVC system would respond in each phase, searching for stabilization at the set voltage. The up and down slopes of the voltage curve (Figure 3b) reflect the arc length variation arising from the AVC actuation. The parameters used in this experiment are given in Table 2.

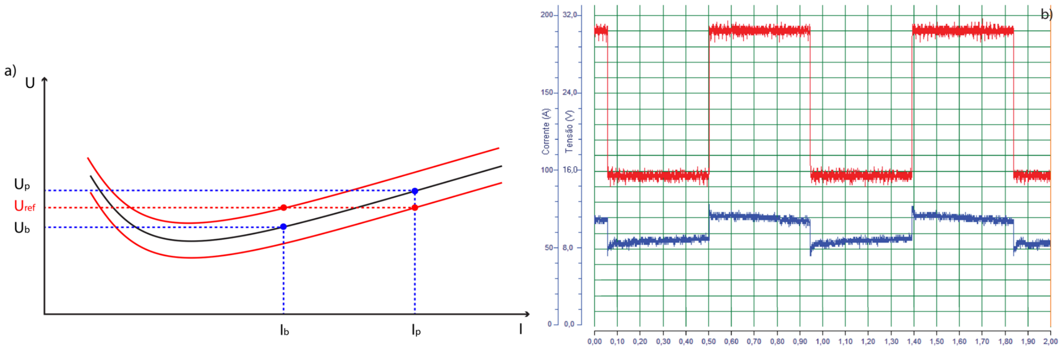

Figure 3. Graphs showing (a) GTAW static curve representation and (b) current (red) and voltage (blue) signal acquisition for AVC based on an average of the pulse and background voltage.

Table 2. AVC based on one reference voltage - test parameters.

Welding currents (pulse / background)	**A**	**190/90**
Pulse and background period	s	0.4/0.4
Travel speed	mm/s	1.7
AVC reference voltage	V	9.3V

Based on the images shown in Figure 4, it was possible to evaluate the variation in the standoff distance between electrode and workpiece (DEP) for each period. The highest value measured was approximately 1.3 mm.

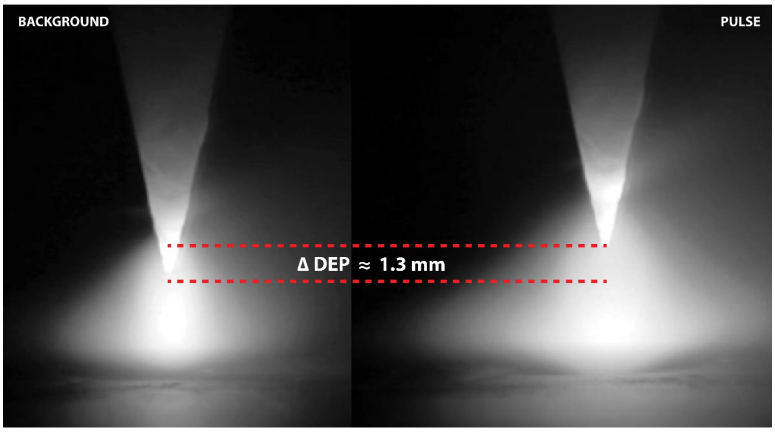

Figure 4. DEP delta between pulse and background periods.

When the reference voltage is set for each phase of the arc, since the static curve or the corresponding voltage for the desired arc length is known, the AVC has a different response for the pulse and background periods, removing the DEP variation. As shown in Figure 5, the up and down slopes present in the previous voltage signals are now replaced with a constant value, with the exception of the beginning of each phase where a voltage overshoot is present. The parameters used for this test are listed on Table 3.

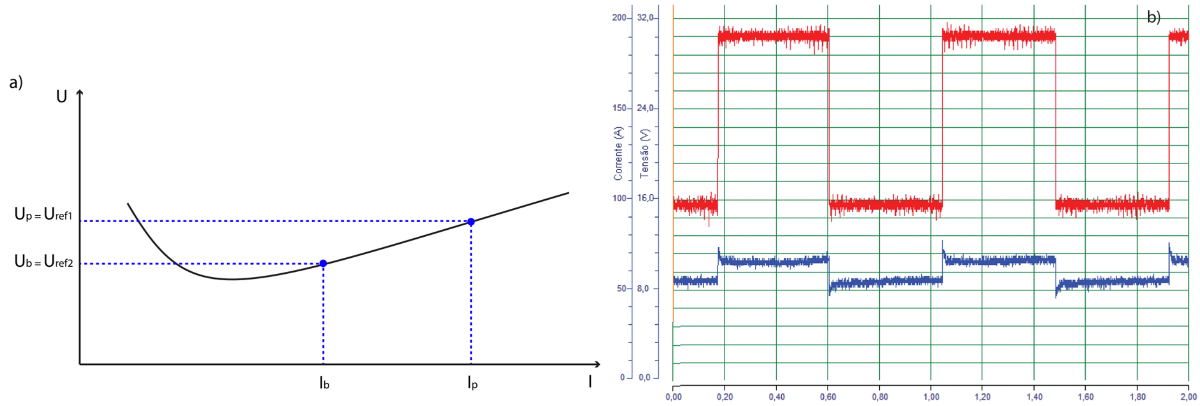

Figure 5. Graphs showing (a) GTAW static curve representation and (b) current and voltage signal acquisition for an AVC based on two reference voltages for pulse and base phases.

Table 3. AVC based on two reference voltages - test parameters.

Welding currents (pulse / background)	A	190/90
Pulse and base period	s	0.4/0.4
Travel speed	mm/s	1.5
AVC reference voltage	V	10.5 / 8.5V

On comparing the arc energy for the two experiments, the difference in the average arc power is negligible. For the first test, with one reference voltage, the acquired data shows an average of 1484 W (2100 W pulse; 890 W background) and for the second test this value is 1500 W (2125 W pulse; 860 W background). Although the difference in the arc power is low, the influence of an oscillating arc is reflected in other instances such as wire feed position and arc pressure. According to Asquel et al. [14], there is a strong relationship between increasing the electrode-workpiece distance and a reduction in the arc pressure. For a 200A welding current, a variation of 1.5 mm in the electrode-workpiece distance reduces the arc pressure by 32%, a value which should not be neglected. The influence of the wire feed methodology will be further discussed.

3.2. On bevel geometry

In automated process, in order to achieve reliability, the joint must be properly prepared to ensure the specified geometry for the procedure. In orbital GTAW, the root face ensures flat contact between the pipes, ensuring zero gap, or a constant gap when desired. Considering the production tolerances of wall thickness and ovalization of the pipe, to keep the root face thickness constant an internal machining operation needs to be carried out. This operation is also known as counterboring. Although this operation aims to maintain the root face equal over the entire end of the pipe, it also creates a difference in the amount of material on the groove land, as shown in Figure 6. Since the roots pass in placed directly over the groove land, the geometry of the latter has directly influence on the former.

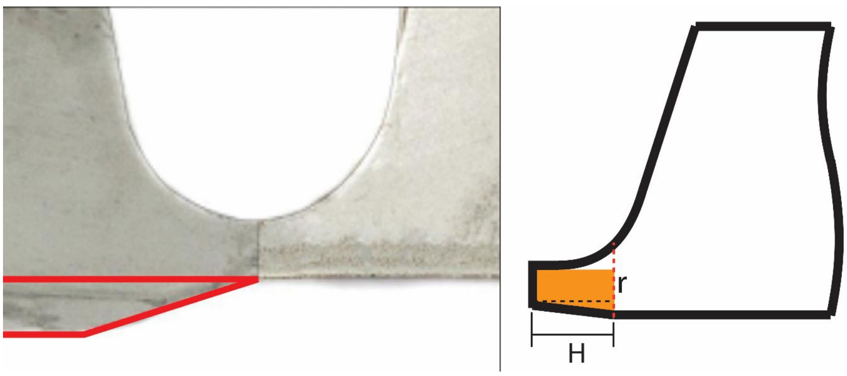

Figure 6 - Bevel geometry of pipes with counterboring operation showing groove land area (orange). and increase in groove land area (red line) with the counterboring operation.

Tracing a reference line (r) parallel to the root face gives the area filled in orange (Figure 6), and the amount of material present increases with the internal taper length (ITL – "H") (Table 4), with expected impact on heat transfer conditions.

Table 4. Influence of internal taper length on amount of material on the groove land.

ITL(H)	0 mm	1 mm	2 mm	3 mm	4 mm	5 mm
Groove land area (mm^2)*	10	11.6	12.9	13.8	14.4	14.5
Increment percentage	0.0%	16%	29%	38%	44%	45%

*From groove face to the reference line "r".

The evaluation of the influence of the ITL was done over a specimen in which the welding was carried out autogenously. In this specimen, the presence of different internal taper lengths was more relevant in the overhead position. The weld parameters used, the weld bead macrographs and the measured molten areas are shown in Table 5, Figure 7 and Table 6, respectively.

Table 5. Welding parameters for autogenous procedures.

Welding currents (pulse/background)	A	210 / 110
Pulse and background periods	s	0.4 / 0.4
Travel speed	mm/s	1.5
AVC reference voltage (pulse/base)	V	10.4 / 8.4

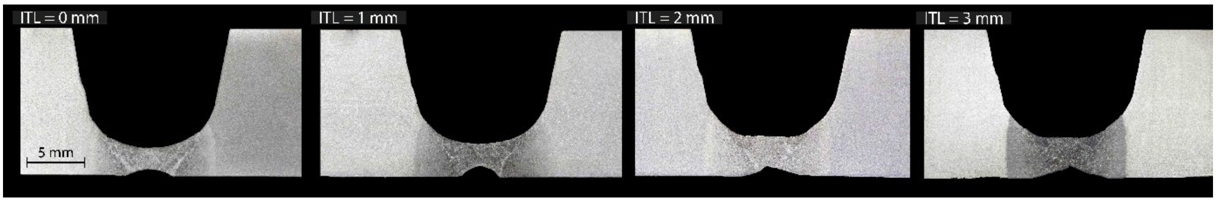

Figure 7. Influence of internal taper length on molten area (overhead position).

Table 6. Decrement of molten area (overhead position).

ITL	0 mm	1 mm	2 mm	3 mm
Molten area (mm^2)	15.1	14.1	12.9	11.2
Decrement	0.0%	-6.6%	-14.5%	-25.8%

The same behavior was observed in another specimen with a different ITL in the flat position. As shown in Figure 8, a decrease in the molten area can be observed as the ITL increases. In this case, the molten areas were 9.7 mm^2, 9.1 mm^2 and 7.9 mm^2 (from left to right).

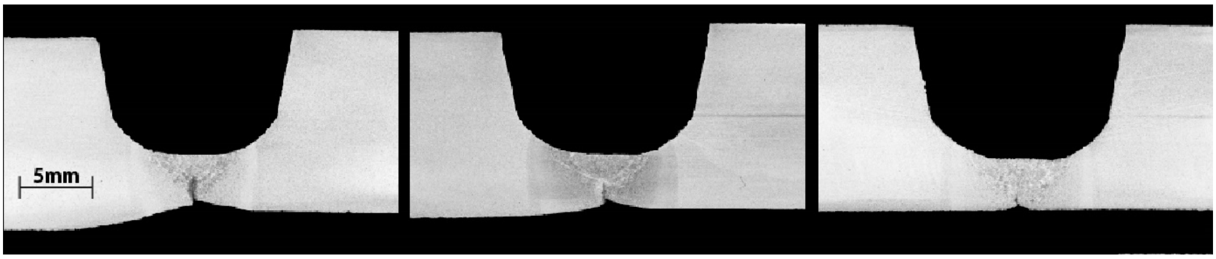

Figure 8. Decrement of molten area (flat position).

According to Figure 7, Figure 8 and Table 6, the decrement of the molten area can be associated to the increase of the ITL. In both positions, it was noticed a reduction of the measured molten area as the amount of material on the groove land increased. Although deeper analysis of heat transfer phenomena was not object of this investigation, it can be inferred that the thermal conduction along the workpiece it is enhanced by higher local material volume, directly influencing on the weld bead cooling, favoring less penetration.

In order to avoid these situations, some beveling equipment's provides an accessory which compensate the pipe ovalization by simply mechanically tracking the internal diameter, shifting the machining tool up and down and ensuring a uniform root face thickness over the entire joint. This accessory is also known as ID-Tracker (internal diameter tracker).

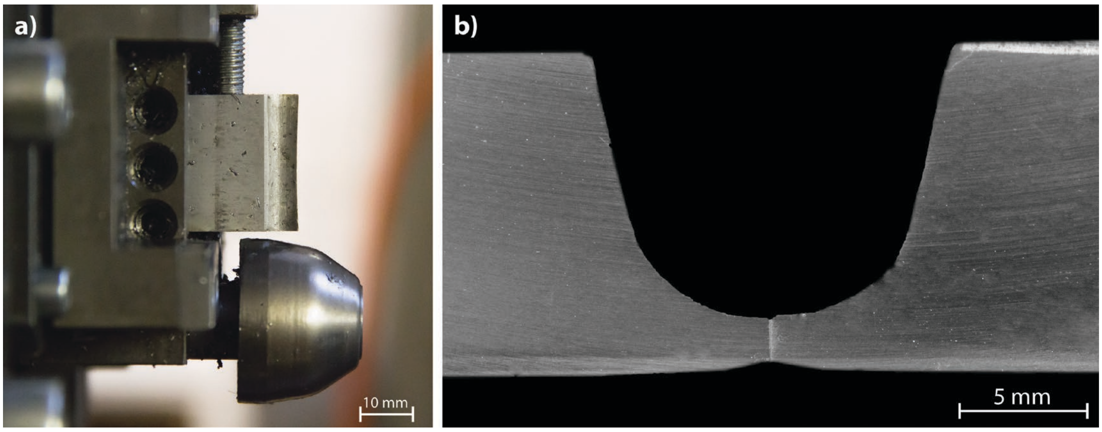

Figure 9. (a) ID-tracker equipped with facing tool and (b) J bevel prepared with ID-tracker accessory.

As shown in Figure 9, the ID-tracker ensures the uniformity of the bevel geometry. The small deformation over the groove face is caused by the forming as the ID-tracker rolls over the internal diameter. Although the presence of this geometry influences the weld bead, since it is present over the entire joint it would not be a problem to parametrize and automate the orbital root pass procedure. The use of an ID-tracker is essential to ensure uniform bevels and fosters successful automated GTAW procedures.

3.3. On wire feed methodology and metal transfer

Another key point in automated GTAW process is the wire feeding technique. In orbital GTAW procedures, the wire feed position, the feeding angle and wire feed speed are parameters which need to be properly determined and controlled to avoid situations such as electrode contamination, lack of fusion or even burn through. Also, the combination of the positioning variables and welding current will determine the metal transfer mode and small variations in any aspect could significantly alter the transfer mode. As can be observed in Figure 10, for a radial wire insertion (angles between 45-60°) a variation of 1.5° could change the bridge transfer mode (a) to intermittent transfer (b), and 3° is sufficient to promote a coarse droplet at the wire tip (c).

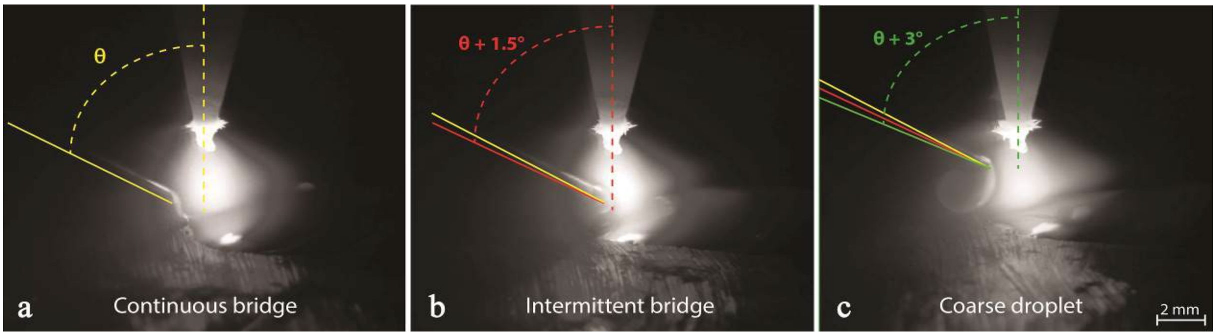

Figure 10. Droplet formations as a function of the wire feeding angle.

Also, the incorrect AVC operation could affect the position of the wire in relation to the arc/electrode. In cases where the wire guider is attached to the welding torch, as in most orbital GTAW welding heads, the up and down movement of the torch occasioned by the AVC leads to different feeding positions of the wire into the arc or molten pool (Figure 11). This situation could be avoided by using two reference voltages for the AVC, as previously discussed. According to Figure 11, if the arc length is too high, the wire is fed into higher regions of the arc. In this case, the wire melts before touching the weld pool, leading to the formation of a coarse droplet on the wire tip, as shown in Figure 10.

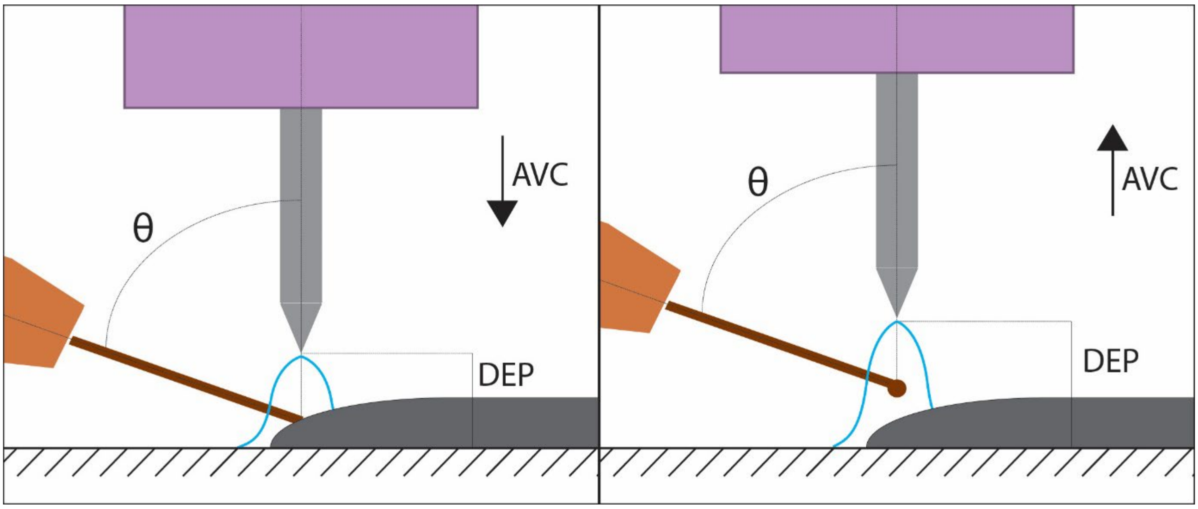

Figure 11. Wire feeding position as a function of the AVC actuation.

Although in orbital GTAW procedures with continuous wire feeding the desirable metal transfer should be the bridge mode, intermittent bridge transfer can also be well defined and controlled. In Figure 12, for continuous bridge transfer mode, the voltage signal remains constant. In a well-defined intermittent bridge transfer, the voltage signal oscillates due to the periodic detachment of the metallic bridge. Also, in Figure 12 (in frames C and D) it can be observed that after contact between the wire and the weld pool the arc anchors on the wire tip, since it would be at the same potential as the workpiece, promoting a small reduction in the arc length and, consequently, in the arc voltage. This phenomenon was also observed by Silva et al. [15], Yudodibroto et al. [7] and Jorge et al. [16]

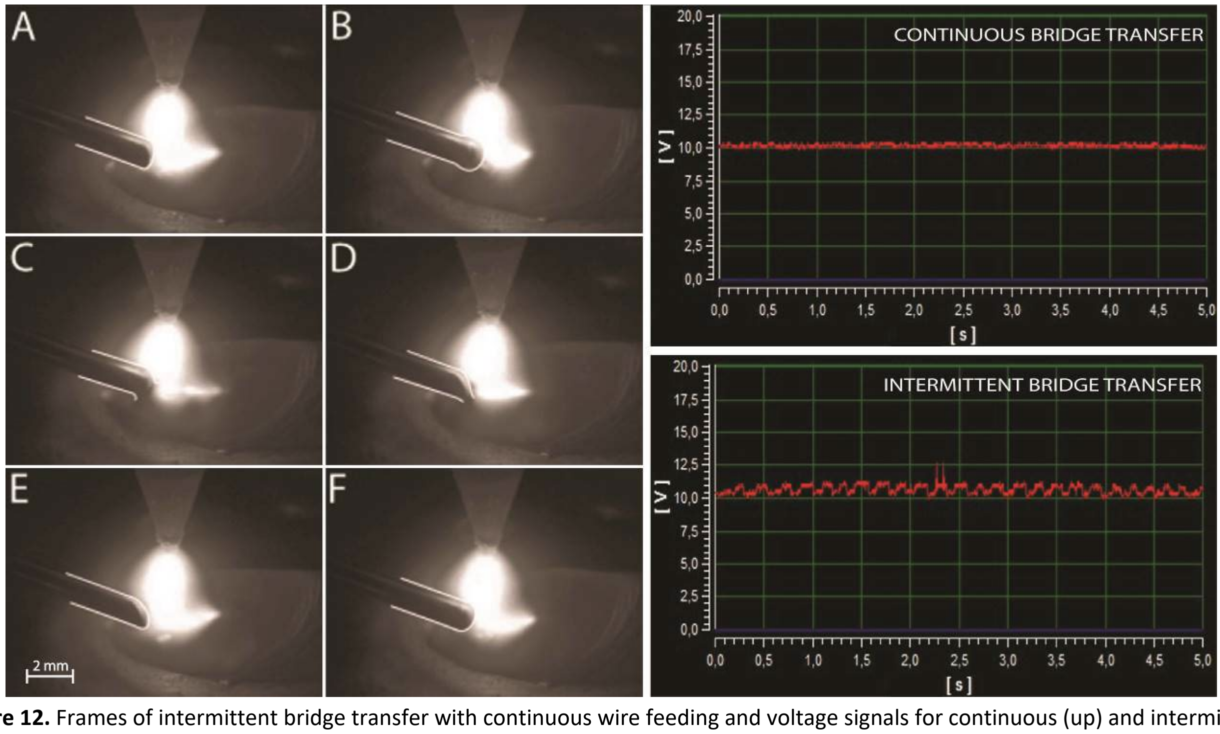

Figure 12. Frames of intermittent bridge transfer with continuous wire feeding and voltage signals for continuous (up) and intermittent (down) bridge transfer modes. A-B: Wire forward movement; C-D: metal bridge consolidation; E-F: metal bridge detachment.

Besides the stability of the process, the type of metal transfer also affects the weld bead. In order to evaluate the influence of the intermittent droplet transfer, the weld bead geometry was compared with that obtained with the bridge transfer mode. As it can be observed from the macrographs shown in Figure 13, in all positions, the weld beads with continuous bridge transfer mode have, on average, 5.2% larger width and 13.3% less penetration. The weld reinforcement, penetration and molten area were, on average, 8.5%, 16.6% and 5.5% respectively, greater with intermittent transfer. Similar results have been reported by Figueirôa et al. [10].

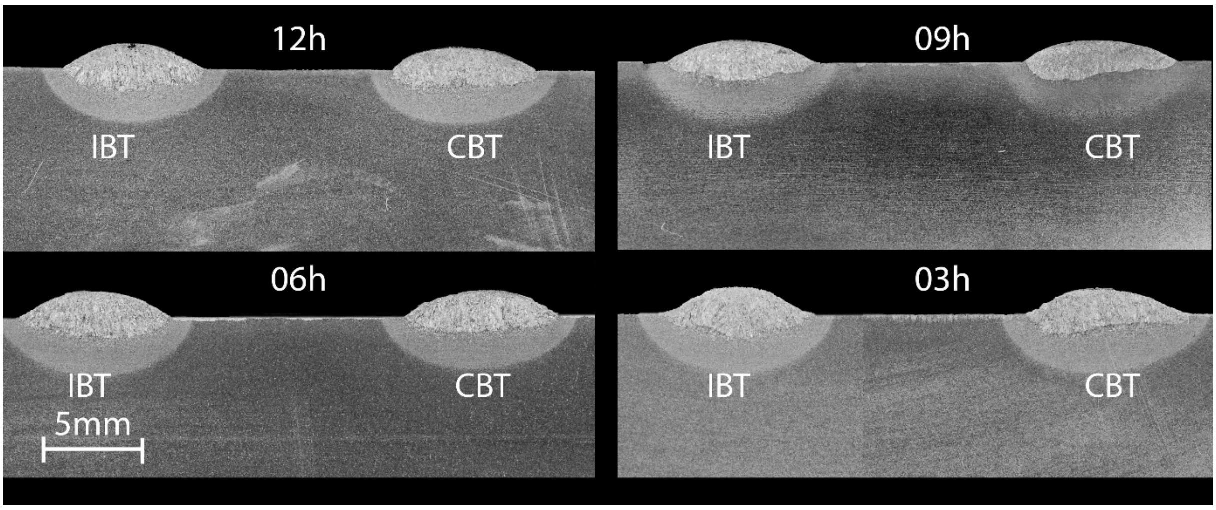

Figure 13. Macrographs obtained to compare the bridge transfer and intermittent transfer modes. (Right weld bead: CBT - Continuous Bridge Transfer mode. Left weld bead: IBT - Intermittent Bridge Transfer mode).

Although the results for intermittent bridge transfer with a continuous wire feed speed showed better geometry for the root pass procedure, this transfer mode is more susceptible to electrode contamination, principally in the overhead and vertical up welding positions. Although there other techniques to avoid the electrode contaminations, such as dynamic wire feeding as suggested by Silva et al. [17], for orbital welding procedures intermittent bridge metal transfer mode should be avoided, and the continuous bridge transfer mode is recommended for continuous wire feeding in GTAW.

3.4. Orbital 360° roots pass procedure

To validate the above considerations, a 360° GTAW root pass procedure was executed over a J beveled joint with no internal taper length. The AVC with two reference voltages was applied and the continuous bridge transfer mode was kept all over the joint. For that, the insertion angle was lightly adjusted as the welding position changed. The parameters used are listed in Table 7.

Table 7. Parameters applied in 360º orbital root pass procedure.

Parameter	Unit	Value
Welding current (pulse/background)	A	180/110
Pulse/background period	s	0.4/0.4
Wire feed speed (pulse/background)	m/min	1.2/0.7
Travel speed	mm/s	1.7
AVC voltage (pulse/background)	V	10.0/8.4
Wire feeding angle	Degrees (°)	~65

As shown in Figure 14, the root pass achieved full penetration over the entire joint. The bevel geometry and joint alignment was uniform at all positions except “10 h” and “8 h”, in which pipe misalignment was present. The weld bead geometry showed considerable uniformity between positions, but it can be noted that from “2 h” (end of vertical up) to “11 h” (end of flat position), the root reinforcement is larger compared with the other positions. The highest value measured was 1.3 mm at the “2 h” position. According to the DNV-OD-F101 Offshore Standard, the maximum acceptable root reinforcement value for pipes of 12.7 mm wall thickness is 2.4 mm. In the vertical down and overhead positions, the weld bead showed root concavity, reaching a maximum value of 0.45 mm in the “7 h” position. In this study, the root concavity was validated by the API 1104 standard (20th Ed. Section 9), and the maximum acceptable value was 1.6 mm.

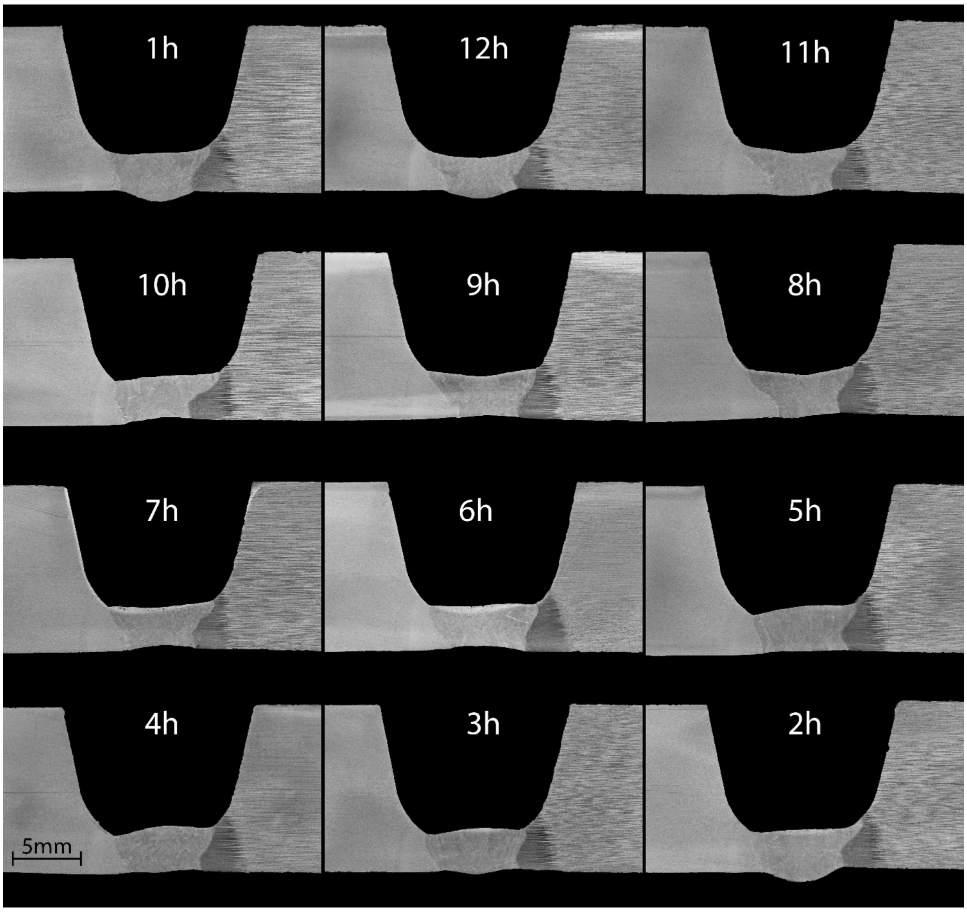

Figure 14. 360º root pass procedure macrographs.

The 360° procedure was executed without changing the parameters and, although the weld bead was acceptable at all positions, it's their geometry differed slightly. For better uniformity of the weld bead geometry along the joint, parameter correction is recommended, principally in the overhead position, which is considered the most critical position.

4. Conclusions

The results obtained in this study provide valuable knowledge concerning pipeline production and the boundary conditions, especially regarding the AVC operation method, bevel geometry and metal transfer. In relation to these considerations, the following conclusions can be drawn:

- Inconsistent AVC operation mode can lead to arc length variations during the welding procedure, whereby, the arc voltage, arc power and arc pressure are affected, potentially compromising the weld bead geometry and integrity;
- For pulsed currents, in order to keep the arc length constant, the AVC must act according to each current level, otherwise the arc length will vary as the current phase changes. Thus, an AVC system based on two reference voltages is more efficient;
- Although the counterboring operation provides a uniform groove face thickness over the entire pipe circumference, the amount of material on the groove land increases as the internal taper length increases. Greater amounts of material in this region reflect in decreased penetration. To avoid this, the bevel machine should be equipped with an internal diameter tracker (ID-tracker), which suppress the need for a counterboring operation;
- For conventional GTAW with continuous wire feed technique, the desirable metal transfer mode should be continuous bridge transfer, since this avoids the formation of a coarse droplet at the wire tip and, consequently, reduces the risk of electrode contamination;
- The metal transfer mode is defined as a function of the filler wire parameters (positioning and speed) and welding currents. The transition from bridge transfer to intermittent transfer is subtle and small variations in any of the variables could strongly effect the metal transfer mode. This spotlights the importance of a suitable, process mode oriented AVC;

- A 360° orbital root pass procedure was achieved without the need for parameter corrections as the welding position varied. Correct AVC operation, summed to a uniform joint and accurate filler wire positioning guaranteed a sound root pass with full penetration in accordance with the relevant standards.

Authors' contributions

IOP: analysis, investigation, writing. RHGS: conceptualization, writing, review. DW: analysis, investigation.

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