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GENERAL EFFECTS OF PULSED COLD-WIRE FEEDING IN GMAW PROCESS WITH SPRAY METAL TRANSFER

[1]Vinicius Lemes Jorge
[1]Fernando Matos Scotti
[1]Ruham Pablo Reis
[1,2]Américo Scotti

[1]Universidade Federal de Uberlândia – UFU, Centro para Pesquisa e Desenvolvimento de Processos de Soldagem – Laprosolda, Uberlândia, MG, Brasil.
[2] University West, Department of Engineering Science, Production Technology West, Division of Welding Technology, Trollhättan, Sweden
viniciuslemesj@hotmail.com, fernandomscotti@gmail.com (FMS), ruhamreis@ufu.br (RPR), ascotti@ufu.br, americo.scotti@hv.se (AS)

Abstract: *Applying pulsed cold wire feeding (P-CW) is one of the new approaches for fusion welding. When applied with the GTAW, this approach is pointed out as a potential way of improving the welding process towards its capability of modifying the weld bead. However, the use of such technique is still unexplored regarding the GMAW process. Thus, the current work is aimed to introduce and evaluate the effect of P-CW for weld bead formation in GMAW. The input angle, position, amplitude and frequency of P-CW were evaluated in bead-on-plate weldments. For analysis purposes three cross sections were cut out of the weld bead. Metallic transfer analysis was conducted and based on tracking the wire tip by means of high-speed shadowgraphy and by monitoring the electric current and voltage signals. So far, the current and voltage oscillograms showed that pulsed wire feeding can interfere in welding process. The dynamics of the wire directly affect the arc characteristic behavior. This characteristic becomes more prominent for lower frequencies and larger angle between the cold-wire and the plate. The metallic transfer of cold wire indicate that larger droplets are formed for smaller frequency. In shallow angle with high frequency the pulsation was able to increase the bead width, followed by a decrease in reinforcement height and penetration. Pulsed cold-wire feeding can interfere in the welding process, opening a field for studies on the application of P-CW to GMAW.*

Keywords: *Pulsed wire feeding; Cold Wire; GMAW*

1. INTRODUCTION

For each traditional welding process, there are multiple variations aiming to improve weld quality, increase productivity, meet particular requirements for applications, or even to enable previously impossible operations. These variations are classified as derivative processes. The major advantage of derivative processes over totally new processes (innovative) is that they are based on an already known and tested platform, and thus having more acceptability by the consumers. The variations frequently involve the development of technologies capable of altering the phenomena occurring in the processes. The methods for adding material in welding processes have been a target of innovation over the past years. Systems capable of promoting pulsed material feeding, i.e., cyclic forward and backward movements to the wire instead of feeding it continuously, have been launched into the market and studied. Silva et al. (2018) described a technique based on this principle and named it as dynamic wire feeding. Volkert et. al. (2018) proposed a system to perform oscillatory feeding of the welding wire based on the principle of operation of a planetary reducer gear. Jorge et al. (2018) developed a system based on an active lung to pulse the wire feeding that works independently from the feeder and/or torch and referred to it as pulsed wire feeding. Rodrigues (2019), also on the topic of pulsed wire feeding, developed a GMAW system with total flexibility of pulsing parameters regulation by the user.

By applying pulsed wire feeding in GTAW, Pike (2013) claims that the technique is capable of improving the weld pool dynamics, giving it more fluidity, and reducing the risk of inclusions and porosity. Moreover, it allowed greater welding speed and deposition rate when compared with traditional (with continuous wire feeding) GTAW. However, the TIP TIG® approach, a commercial equipment, shown disadvantages when compared to manual TIG regarding joints with limited accessibility and operation in confined spaces. Silwal and Santangelo (2018) evaluated material feeding in GTAW with cold-wire and hot-wire, using continuous and pulsed wire feeding. A pulse frequency of 16 Hz was applied. The effects observed on metallic transfer and bead formation were more related to wire heating than to the use of pulsation. In another work, by Santangelo et al. (2016), it is indicated that hot-wire can be applied coupled with pulsed feeding in order to achieve more uniform depositions with potential application for additive manufacturing. Watanabe et al. (2010), in a related study, investigated the use of ultrasonic vibration in GTAW filler wire. In this case vibration was applied in the direction transverse to the welding direction and it was found that the filler metal vibration could be transmitted to the weld pool and, by that, increase in tensile fracture elongation of the resulting weld metal. This type of vibration was capable of influencing the droplet detachment rate, which was considered as beneficial for high speed welding and arc-based additive manufacturing for large metallic structures.

As pointed by Silva et al. (2018), despite the studies that have been developed, the whole physical fundamentals of pulsed cold wire feeding behavior on GTAW have not yet been stablished. In their studies, with low frequency (0 to 2 Hz), they tried to clarify some facts on metallic transfer and weld pool temperature gradient. For instance, they verified that the possibility of transferring the metal inside the weld pool itself is an advantage for out-of-position welding. Jorge et al. (2018) has shown that pulsed feeding has the potential to interfere in the process, improve the droplet transfer regularity and modify the weld bead aspect for the GTAW as well as for the GMAW case. Silva et al. (2019b) demonstrates the feasibility of pulsed cold wire feeding for orbital welding, aiming at root pass with the GTAW process. This technique improved metal transfer and contributed to productivity without instabilities. Silva et al. (2019a) reveals that the large droplets in continuous feeding result in less robustness and bead surface asymmetry, while dynamic cold wire feeding produce more symmetric weld beads and more robust processing.

On the other hand, the use of cold-wire in the GMAW is also applied in order to increase deposition rate without increasing heat input to the joint. Beyond these characteristics, Ribeiro et al. (2015) showed that cold wire introduction allows a slight increase in welding current without consequent increase in penetration. When compared with conventional GMAW, CW-GMAW features increased deposition rate and distinct variation in the geometric features of the bead, such as bead penetration and dilution rate. Assunção et al. (2017) showed that cold-wire feeding was able to reduce discontinuities in weld beads produced with such a process, besides increasing productivity. The authors claim that the cold-wire leads to changes in the heat transfer to the base metal, which can improve the HAZ microstructure and hardness. Costa (2018) pointed out that cold-wire addition reduces residual stresses while decreases heat input to the plate. Ribeiro et al. (2019) investigated metal transfer dynamics and its influence on dilution and melting efficiency for short circuit, globular and spray transfer modes. The authors showed that the cold wire addition leads to changes in arc position in the longitudinal axes (along the welding direction). This variation entails cold wire energy absorption capacities. However, the use of pulsed cold-wire feeding in GMAW, i.e., with an extra filler material that is not energized as the GMAW electrode-wire, have not been explored yet. Thus, the current work aimed to introduce and evaluate the effect of pulsed cold-wire feeding for weld bead formation in GMAW, specifically with spray metal transfer.

2. EXPERIMENTAL PROCEDURE

For this study GMAW process with pulsed cold-wire addition was used. Bead-on-plate welding was carried out on ASTM 1020 test plates of 270 × 31,8 × 9,53 mm. An AWS ER70S-6 wire was used for the electrode-wire and also for the cold-wire. An IMC Digiplus A7 power source was used for welding with the GMAW in constant voltage mode. An IMC system was used to feed the cold-wire. The wire feeding pulsation was done by a device developed at Laprosolda-UFU which is based on an "active lung" mechanism (Jorge et al., 2018). This device can be coupled to any conventional feeder. Data acquisition (electric voltage and current) was carried out by an A/D board at a rate of 5 kHz and 14 bits, for 40 s in each run. Synchronized to data acquisition, each run was filmed using a high-speed camera operating at 2000 frames/s, with shutter speed of 1/200000 s. A He-Ne laser (632.8 nm wavelength) was used for back-lighting and a narrow band pass optical filter (632.8 ± 5 nm wavelength range) was used to block the arc light. The experiment design was according to Table 1. The general welding parameters are shown in Table 2. The cold-wire feed speed was selected so that maximum deposition rate was achieved while the arc was still able to fuse the extra wire and result in a bead with sound superficial aspect. This way, a bridge-like metallic transfer mode was assumed to take place from the cold wire to the weld pool. For runs from 1 to 7 the ratio between the cold wire volume and total deposited volume corresponds to 36.2%. For runs 8 and 9 cold wire feeding was not applied. On run 8 all the other parameters were kept the same and for run 9 the welding speed was decreased, so that the deposition rate was equivalent to the runs with cold wire addition. The pulse amplitude of the wire movement was 7 mm for all the pulsed runs, ensuring the wire would exit and enter the weld pool cyclically. Two different angles between the cold-wire and the plate were tested for a fixed separation between the cold wire extension at the plate level and the electrode-wire tip used, as shown in the experiment rig (Figure 1) represented by Θ. For analysis purposes three cross sections were cut out of each weld bead. With the surfaces prepared and chemically attacked with Nital 10%, the bead width, penetration, reinforcement, molten area and dilution were measured.

Table 1 - Pulsed cold-wire parameterization

Run	CW Enabled	Welding Speed (cm/min)	Θ (degrees)	Frequency (Hz)	Amplitude (mm)
1	Yes	35	15	-	-

2	Yes	35	15	3	7
3	Yes	35	15	4	7
4	Yes	35	15	16	7
5	Yes	35	45	-	-
6	Yes	35	45	4	7
7	Yes	35	45	16	7
8	No	22,4	-	-	-
9	No	22,4	-	-	-

Table 2 - General welding parameters

Parameter	Value
Voltage (V)	30,5
Electrode-wire feed speed (m/min)	7.7
Electrode-wire diameter (mm)	1.2
Contact-tip to work distance - DBCP (mm)	18
Cold-wire feed speed (m/min)	6
Cold-wire diameter (mm)	1.0
Gas flow rate (l/min)	17

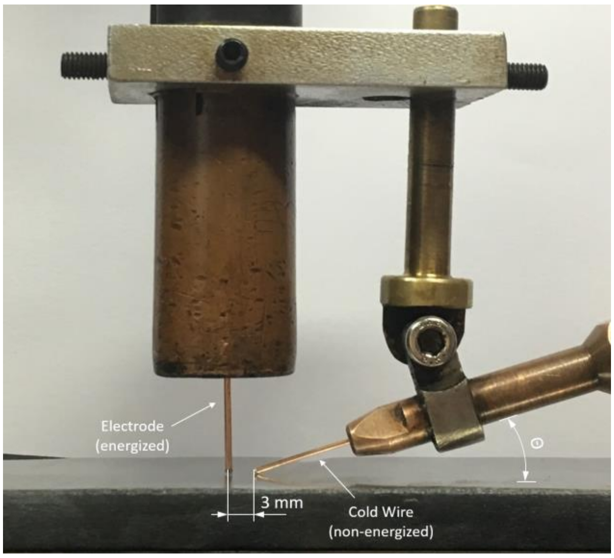

Figure 1 - Cold-wire feeding angle and electrode-wire to cold-wire distance

3. RESULTS AND DISCUSSION

3.1. Electrical signals

According to Figure 2, runs 1 and 5 (continuous cold wire feeding) showed no significant changes in the current and voltage oscillograms by changing the cold wire input angle. On the other hand, a change on the current wave form can be seen when pulsed cold wire feeding (P-CW) was applied. The oscillograms follow up the dynamics of the wire according to the imposed pulsing frequency. This characteristic becomes more prominent for lower frequencies and larger angle between the cold-wire and the plate (Θ). The arc length internal control is a widely known phenomena on GMAW process with constant-voltage power sources. The situation shown in Figure 3(A) represents a torch travelling linearly over a plate. In the first moment (1), according to the welding parameters and conditions set, an arc is stablished and assumes its own static characteristic curve. The constant voltage power source has its own static characteristic curve and the intersection between both curves determines the process operating point (1). As the torch finds a step following the welding direction, in moment (2) the arc length is momentarily reduced and the arc assumes a new static characteristic and a new operating point (2). There is no significant change in voltage, but current increases instantly, consequently increasing wire melting rate. Since feeding rate is kept constant, the wire will be consumed faster, leading the arc length to increase. In moment (3) the arc length is reestablished to a condition similar to the initial one and so does the current. It must be noticed that since the contact-tip to work piece distance has been decreased, the current will be slightly larger than in the original condition.

When working with pulsed cold wire feeding two typical moments can be distinguished as shown in Figure 3(B). In the first moment the arc is at maximum retreat position and it remains completely over the weld pool, establishing operating point (1). In the second moment the wire is at the maximum advance position and the arc remains partially over the wire establishing operating point (2), where the current increases due to the effect of the cold wire under the arc. Since the wire advances and retreats cyclically, the current will keep going up when the wire enters the arc region and going down when it leaves it as seem in Figure 4. By drawing a parallel scenario between the situations shown in Figure 3(A) and Figure 3(B) the input of the cold wire can be understood as the cyclical imposition of a rising step under the arc.

On the difference between pulsed wire feeding at 4 Hz with 15° and 45° input angles (runs 3 and 6) it is noticeable that the mean current value is higher for 45°. To better understand the dynamics of the wire in relation to the arc, Figure 5 (B) represents the paths traveled by the wire cyclically for each situation. The distances d1 and d2 are the distances traveled outside and inside the arc influence regions, respectively. One can notice that at 45° (2) d2 is larger when compared to the case at 15° (1). Going back to the step analogy mentioned previously, at 45° the wire imposes a larger step (Figure 5(A)), leading to a lower transient arc characteristic curve and a consequent increase in current. This can be verified by looking at the larger amplitude in current oscillation for run 6 (Θ = 45°) when compared to run 3 (Θ = 15°). The ratio between distances d1 and d2 justifies the difference in the curve symmetry in relation to the average for runs with 15° and 45°. In runs 3 and 4 the wire spends more time outside the arc influence region, thus presenting the lower current transients, whereas on runs 6 and 7 the wire has a better balance between inside/outside arc times, but still with more time inside the arc, justifying the upper current transients. For runs 4 and 7 (16 Hz frequency) the differences due to the input angle are still noticeable. However, the oscillation amplitudes are lower. Since the wire moves faster, the dynamic response of the power source has less time to raise the current.

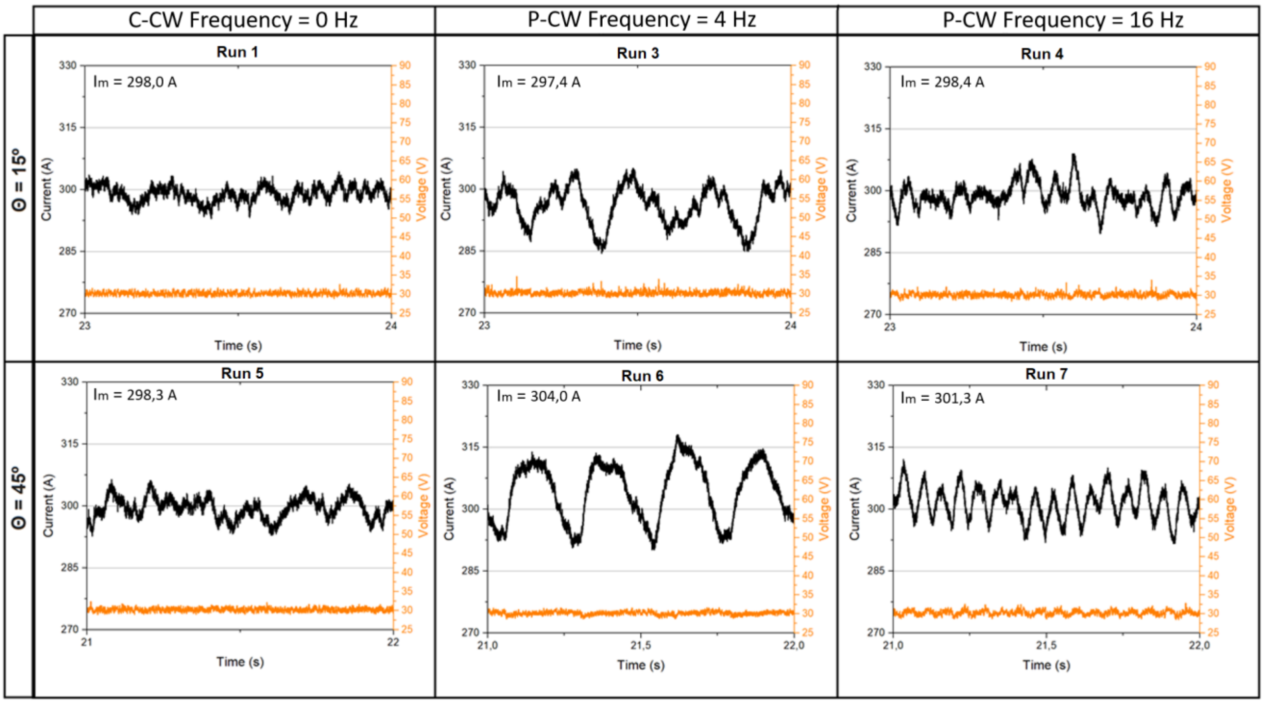

Figure 2 - Electric current and voltage oscillograms surveyed: First line for runs 1, 3 and 4 respectively from left to right; Second line for runs 5, 6 and 7 respectively from left to right (Im is the mean current value)

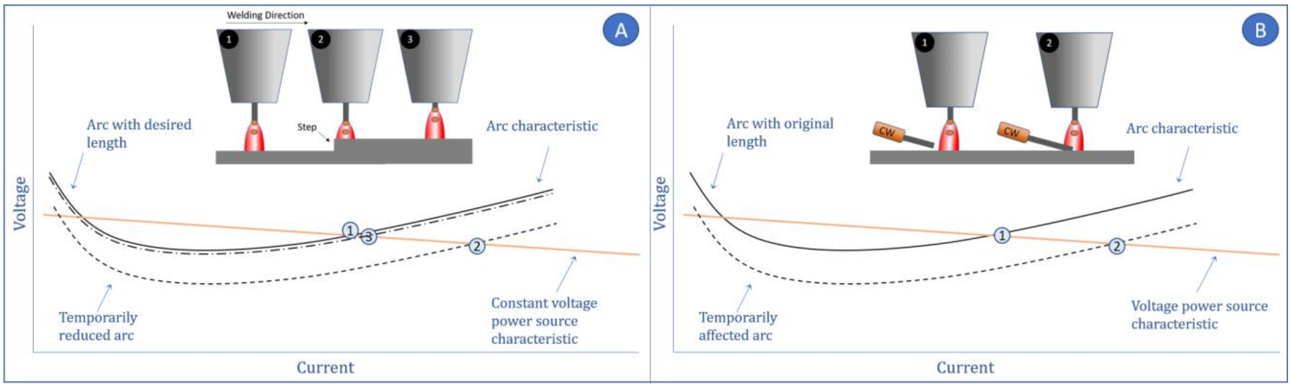

Figure 3 - Illustration of the arc length control phenomenon using constant voltage power source. (A) Typical situation of temporary reduction of arc length; (B) Relationship between retreat/advance position of the wire in P-CW and arc characteristic behavior

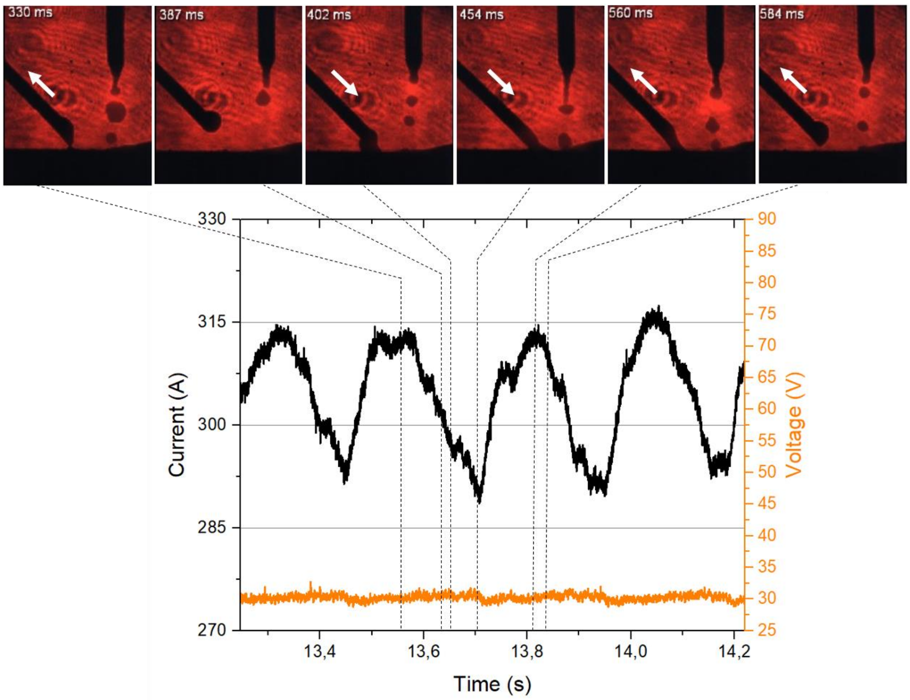

Figure 4 - Synchronization between cyclical cold wire advance and retreat movements with the voltage/current behavior

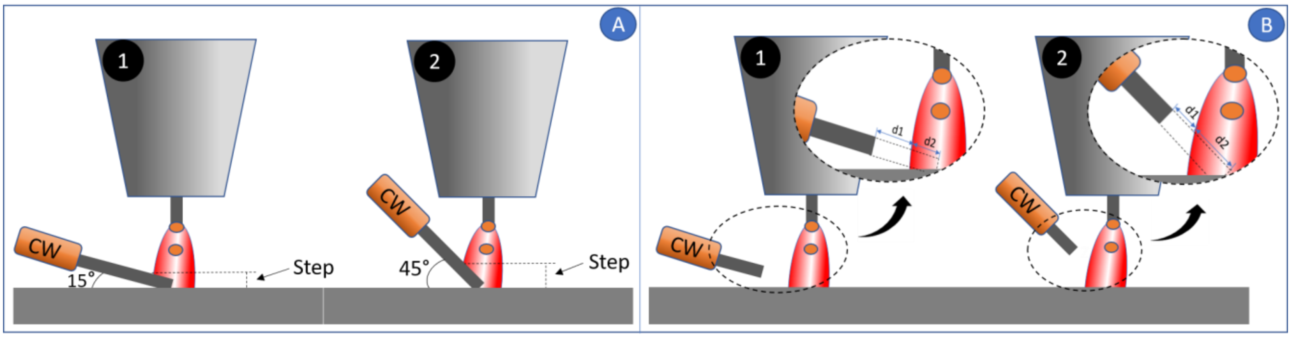

Figure 5 - (A) Relationship between CW input angle and "step" imposed to the arc; (B) Relation between CW input angle and the wire distance traveled outside (d1) / inside (d2) the arc influence region

3.2. Metallic transfer

Figure 6 shows selected frames from the high-speed filming at maximum and minimum advance position with wire input angles at 15° and 45° (Θ) and with the pulsing frequencies at 0 Hz (C-CW), 4 and 16 Hz (P-CW). For runs with C-CW a similar situation can be observed at both input angles. It shows that a bridge metal transfer from the cold wire to the weld pool was stablished throughout the weld process. By analyzing the P-CW runs, two moments are distinguished. First, when the pulsing mechanism is at the maximum retreat position (first line of images in Figure 6), the cold wire loses contact with the weld pool. In the second moment, when the mechanism is fully advanced (second line of images in Figure 6), the cold wire goes into the weld pool and transfers the previously formed droplet at the wire tip along with its molten partial body. At Θ = 15°, it is noted that a larger droplet is formed when the P-CW frequency is at 4 Hz when compared to case with 16 Hz, which might be justified by the fact that in this situation the wire spends more time under the arc influence, without touching the weld pool. At Θ = 45°, a larger portion of the wire stays under the arc influence when compared to the case with Θ = 15°. A deformity can be noticed in the wire at the maximum retreat position for 16 Hz P-CW. It must be highlighted that this phenomenon repeats itself each advance and retreat cycle. Since in this case the frequency is higher, the movements are more abrupt, dislocating the formed droplet upwards the wire.

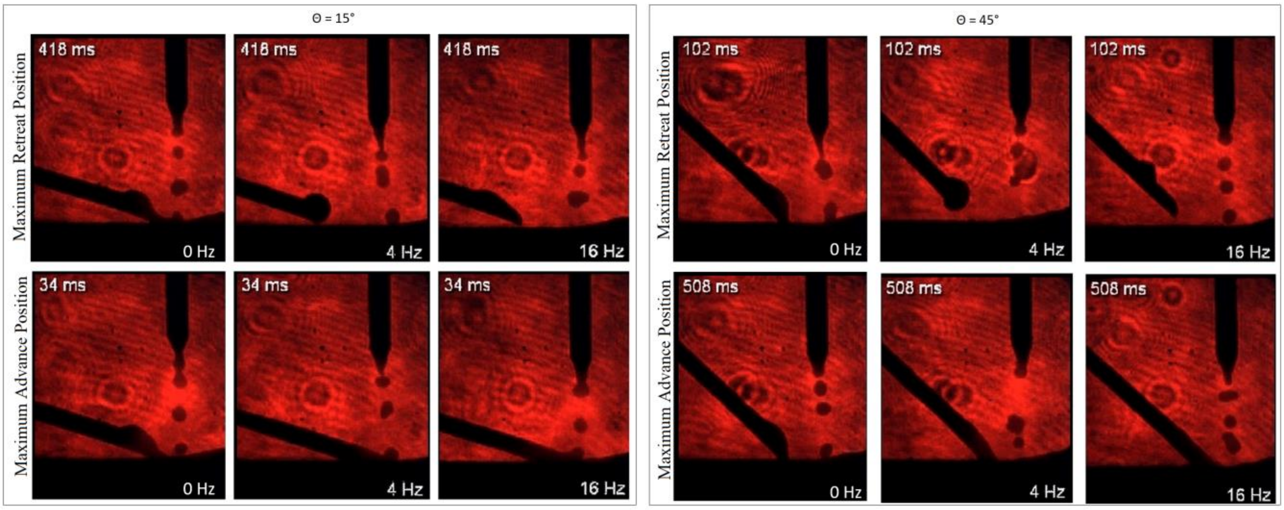

Figure 6 - Typical metallic transfer behavior observed. On the left-hand side: runs 1, 3 and 4 respectively from left to right; On the right-hand side: runs 5, 6 and 7 respectively from left to right.

3.3. Cross Sections and Weld Bead Geometry

Figure 7 shows the mean values of width, penetration, reinforcement, fused zone and dilution for the weld beads obtained through the runs described in Table 1. It can be observed that width and penetration are larger with conventional GMAW when compared to continuous CW-GMAW (C-CW: Θ = 15 and 45°). From the thermal and energetic point of view this is expected, since in CW-GMAW part of the energy provided by the process is demanded to melt the additional wire. The inferior temperature levels imply less wettability and thus justifies the larger reinforcement. From the mechanical point of view, the larger weld pool volume hinders arc digging action, attenuating the typical mechanical effect of droplet impact with spray transfer, justifying the decrease in penetration. On the other hand, when pulsed wire feeding was applied (P-CW-GMAW: Θ = 15 with 16 Hz; P-CW-GMAW: Θ = 45° with 4 e 16 Hz), the width values became close to those found with GMAW, but still with less penetration. The hypothesis is that the exiting and entering movements of the wire into the weld pool affects its surface tension, enhancing the wettability. In this case, the liquid metal spreads more easily, justifying the increase in width. By looking at the case in which the GMAW process was conducted with a deposition rate equivalent to that of the CW-GMAW (EPR GMAW), penetration, width and fused zone are expressively larger compared to the other conditions. This fact might be attributed to the greater welding energy employed and consequent heat input.

For P-CW-GMAW: Θ = 15 with 3 and 4 Hz no significant changes in weld bead geometry are noticed when compared to continuous feeding. However, when 16 Hz pulsation was applied, an increase in width, followed by a decrease in reinforcement and penetration, can be noticed. A hypothesis for this behavior would be that for low input angles the vibration caused by the higher frequency can shake and spread the weld pool towards the transversal direction. For P-CW-GMAW: Θ = 45°, there is no significant change regarding penetration for the evaluated frequencies. A decrease tendency can be noticed on weld bead width when increasing the pulsing frequency. Adding cold wire to GMAW, in a continuous or pulsed fashion, reduces dilution drastically when compared to GMAW and EDP GMAW runs. There is no evidence that pulsed cold wire feeding can cause significant changes in fused area and dilution.

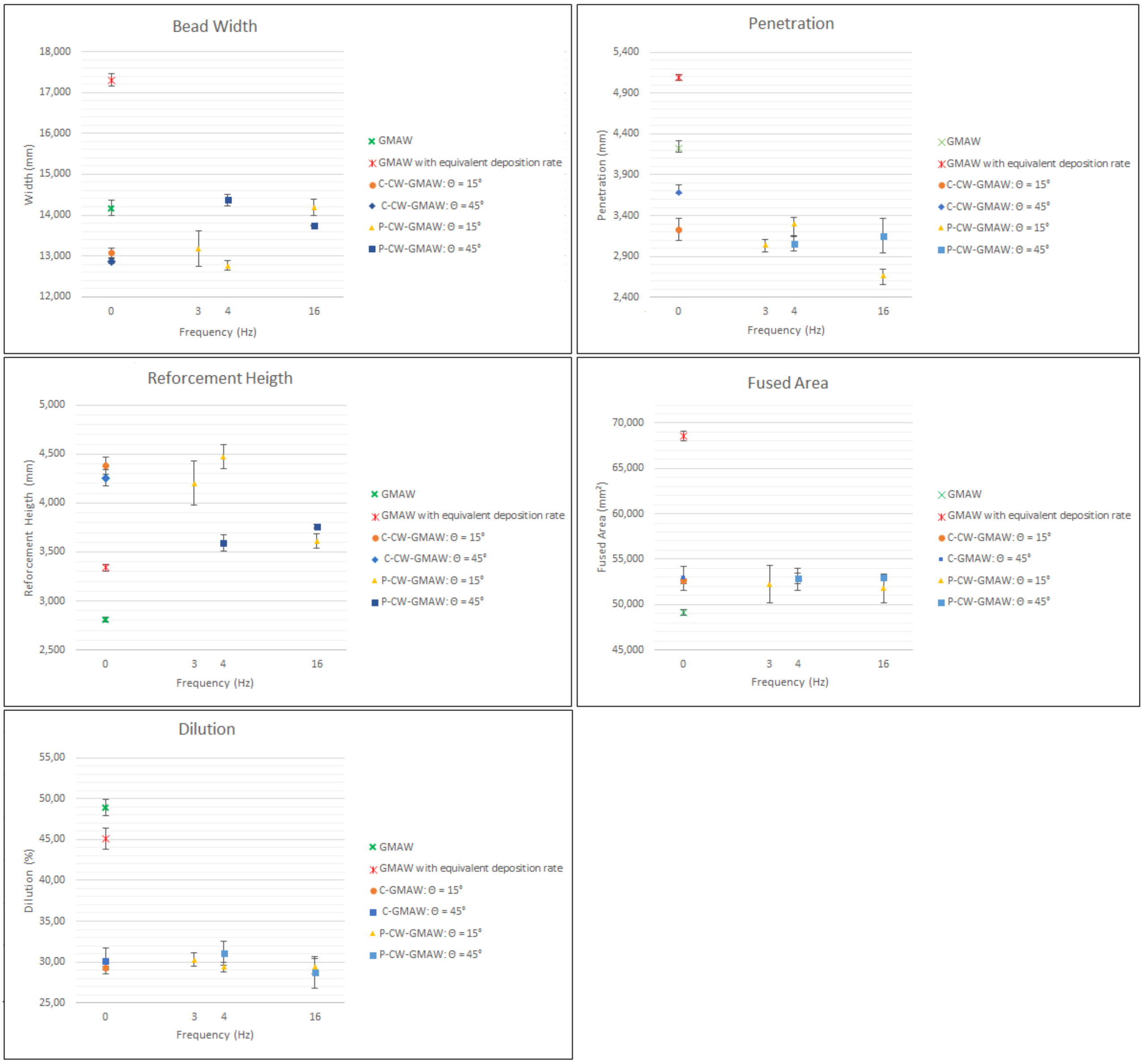

Figure 7 - Geometric features of the weld beads (average of three cross-sections)

4. CONCLUSION

This work presents the potential of pulsed cold wire feeding to affect electrical signals and bead formation when compared to conventional cold wire feeding. The current signals behavior follows the dynamics of the wire pulsation in accordance to the arc internal control phenomenon. The droplet geometry and transfer formed on the cold wire were also affected by pulsation.

Regarding bead formation, a bead with wider bead with less penetration was achieved when the pulse frequency was 16 Hz and the entry angle of 15º, as well at 45 º with 4 and 16 Hz. The comprehension of the whole phenomena involved in bead formation with pulsed cold wire feeding still require further investigation. However, the results opens new opportunities on studies related to P-CW on GMAW aiming specific applications.

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