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Comparative study of heat input in conventional and advanced short circuit GMAW variants

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Abstracts

Due to its varied range of applications, the short circuit GMAW process is highly used in the industry. Among the welding processes available in the market, this one stands out for delivering low cost and high productivity, being commonly used in naval field as root pass and also in additive manufacture for turbines production. Nevertheless, the heat input applied for this process is one of the main challenges when regarding applications where sensitive materials are used and precision is required, since high temperatures imply residual stress and possible structural damages. Therefore, the short circuiting metal transfer technologies developed by different companies are tested to study their methods to control the temperature in the welding process. This knowledge may help to understand the influences of the parameters and, then, to parameterize the process and select a technology among so many available in the market. The processes divided in standard, electrically controlled and retractable wire feed short circuit are used to produce a weld bead with similar geometry and have their performance analyzed developing the same task. As one of the most recent applications of modified short circuit GMAW, an exploratory additive manufacturing test is developed with three different processes to compare their methods and performances. The electrical parameters of each process are measured and the theoretical heat input is calculated and compared. A macrograph of the result weld beads is made to analyze the penetration and its relation with the deposition. It was observed throughout the heat input and penetration areas comparison that the theoretical heat input does not describe the physical performance of the processes. Some samples showed higher theoretical heat input and smaller penetration than others. Therefore, the physical performance can be better predicted by observing the process electric waveform, where drop detachment frequency, power peak and low current intervals are very influential. The standard short circuit processes showed the highest penetrations, followed by the electrical controlled processes. The retractable wire feed processes showed the lowest penetration values. In the theoretical heat input measured was not possible to observe significant advantages between the electrical controlled and standard processes, with exception for the ECP 2 technology. The retractable wire feed processes had the best results in the metrics, showing the lowest theoretical heat input and penetration. The preliminary AM procedure showed a big range of geometry changes, with the retractable wire feed processes controlling better the heat input, leading to a more continuous part.

1. Introduction

The short circuit welding process, placed in the low power range of Gas Metal Arc Welding (GMAW) (Kah, 2021; Kim & Chung, 2017; Norrish, 1992), is widely used in the industry due to its union of easy handling, high productivity and low cost (Pattanayak & Sahoo, 2021; Norrish & Cuiuri, 2014). This makes the GMAW very suitable for a big range of applications. However, the relatively high heat input generated by this process poses a challenge, since the temperature of the process can affect the mechanical properties of the material used. This creates residual stress and distortions in the part welded (Feng, 2005), being critical in several applications, like additive manufacture, where precision is necessary, and copper welding, that has low oxidation resistance for high temperature. Burn through of the welded part, especially for thin sheets and root passes, is also an issue to be addressed. Therefore, the control of heat input in the short circuit process was studied by the companies in the field, creating different methods to reduce the temperature in the welding process, each one with its specific characteristic.

To analyze influence from different power sources producing the same weld, Joseph at al. (2005) tested four power sources from different brands. In the tests the same base parameters were used to develop the weldings of V joints. The results showed a big variation range of weld bead width, height and current peaks. Also, the heat input shown by the power sources had a 17% gap between the higher and the lower heat inputs presented, showing that, even for the same parameters, the weld results differ considerably.

Chaudhari et al. (2022) developed a study of the most influential parameters for the geometry of weld bead width and height. In the tests, they varied the wire feed speed, welding speed and voltage. It was observed that the most influential parameter for both, width and height, was the wire feed speed, followed by welding speed and voltage for width, and voltage and welding speed for height, in this order. Indeed, Kumar et al. (2021) showed in their work that the shielding gas flow rate does not affect the geometry of the weld bead, however is relevant for the heat input, since the heat transfer capability of each gas is different.

In his work, Silva (2005) compares the standard GMAW short circuit process and an electrical controlled process to observe their behavior regarding heat input, penetration and spatter. The same wire feed speed and welding speed were used for both processes. Against shown by the literature, the heat input by both processes had not a significant difference, with the electrical controlled short circuit having slightly less heat input. He also presented a relation between drop volume and penetration, where the bigger is the drop volume, higher is the penetration. It was attributed to the longer arc time acting over the sample. In the same line, Filho et al. (2013) compared three different short circuit methods: standard, electrical controlled and retractable wire feed processes using the same wire feeding speed. The result was a much wetter weld bead presented by the standard short circuit method, with the other two with a convex weld bead. They also pointed to the drop temperature as the main responsible for the penetration in the short circuit processes. The arc temperature influences more in the weld bead wettability (Esser & Walter, 1980).

Since there are several power source brands in the market, each one with its own methods to produce and shape the waveform and control the short circuit welding, the present work aims at a comparison of the heat input from the welding process using different short circuit technologies. The objective is to provide a deeper and independent knowledge base from the influences of parameters imposed by the modified GMAW short-circuiting processes and, consequently, support not only the selection of one technology among so many available in the market, although also the parameterization of the process for different applications and conditions. A secondary objective was a preliminary assessment of the modified short-circuiting GMAW variants performance for AM. All the processes are parametrized to produce a weld bead with defined geometry, have their power calculated and macrographs analyzed to observe the impact of method characteristics developing the same task.

2. Materials and Methods

2.1. Materials used

The welds were made in a substrate of mild steel S235JR, cutted with 100 mm length, 20 mm width and having 8 mm of thickness. The wire was type EN ISO 14341-A G 3Si1 with 1,2 mm of diameter and the gas used was an ISO 14175 - M12 ArC-8 with 15 l/min of flow.

2.2. Equipaments

The power sources used had their short circuit variants divided in three groups: standard process (SP), electrically controlled process (ECP) and retractable wire feed process (RWF). Six different power sources were used in total, although their name is not cited since the goal is comparing the results generated by different short circuit methods. Brands are not compared.

Auxiliary equipments used are listed below:

- OTC FD-V8L robot OTC FD19 controller;
- ABB IRB 2600 robot IRC5 controller;
- Cloos robot xyz;
- ATM/QATM machine model Carot 930 microscope.

2.3. Methodology

The work aims at a comparative study of the performance and results of different technologies of the short-circuiting GMAW process. For this, the goal is to produce a weld bead with the same geometry with all the short circuit variations available, being able to compare all the processes' performance developing the same task. The weld bead geometry sought is shown in Figure 1.

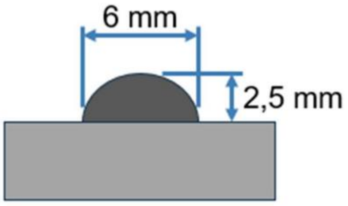

Figure 1 – Weld bead geometry sought

The substrate is fixed in the table, the arc is started above and the table moves forward, keeping the torch still during the welding process. For all the welds, it was used welding speed of 0,4 m/min in the table and stickout of 10 mm. The parametrization process ends when the weld bead reaches the geometry sought. This process is repeated with all the short circuit variations.

The processes are compared with the theoretical heat input calculation and the area ratio. The theoretical heat input is calculated using the effective power, P_{eff}, which is defined by Equation (1) (Dutra et al., 2013). The Equation (2) is used to calculate the liquid theoretical heat input, defined by H_{net}, based on average power, welding speed of WS = 6,667 mm/s and a correction of process efficiency, approximated by the literature by η = 0,8 for short circuit (Arevalo & Vilarinho, 2012). With the help of macrographs, the area ratio calculus consists in the division of the weld bead cross section in two areas: the additional material area, named A1, and penetration areas, named A2. The Equation (3) shows the area ratio calculation and the interesting areas are illustrated in Figure 2.

$$P_{eff} = \sum_{i=1}^{n} \frac{I_i * V_i}{n} \quad (1)$$

$$H_{net} = \frac{P_{eff} * \eta}{WS} \quad (2)$$

$$Area\ ratio = \frac{A_2}{A_1} \quad (3)$$

Figure 2 – Illustration of penetration and additional material areas

3. Results

3.1. Short circuit process variations

All the processes chosen work with short circuit method, belonging to the low power range of GMAW (Kah, 2021; Kah et al., 2013). These process variants are divided into: standard short circuit, electrically controlled and retractable wire feed. The standard short circuit is characterized for, theoretically, having no kind of control to modulate the metal transfer, nor to reduce the power used. On the other hand, the electrical controlled and retractable wire feed processes exert active online parameters adjustments over the short circuiting metal transfer in order to control the welding power and, with this, control the heat input of the process. Arc stability and spatter reduction are sought after benefits as well.

In Figure 3, Figure 4 and Figure 5 are shown the electrical oscillograms of the three different types of short circuit variations observed, the standard short circuit, electrical controlled and retractable wire feed processes, consecutively.

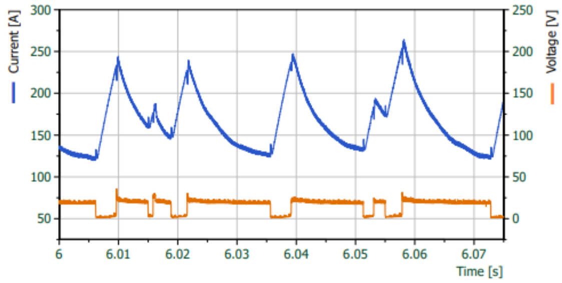

Figure 3 – Standard short circuit

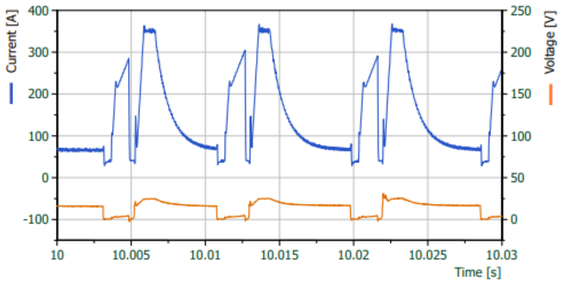

Figure 4 – Electrically controlled process

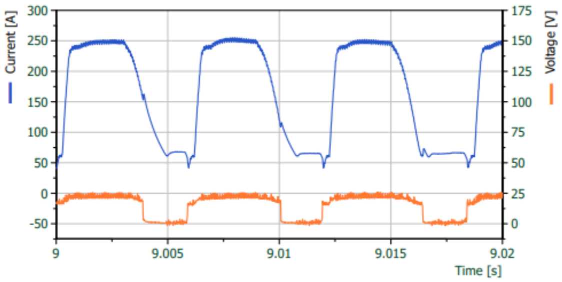

Figure 5 – Retractable wire feed process

The standard short circuit can be characterized for its sequence of: drop formation, melting the wire with the electric arc; contact between drop and melt pool, caused by the continuous approximation by the wire to the pool; drop detachment by power peak, caused by the pinch effect that acts to impel the drop and release it in the melt pool; and the arc reignites, caused by the potential difference after the wire and melt pool disconnection (Kah, 2021; Norrish & Cuiuri, 2014).

The electrical controlled processes, in turn, follow the same steps, forming the drop, approaching the drop to the melt pool, releasing the drop and the process restart. However, as can be seen in Figure 4, the process of drop detachment is modified, separating the drop impelling, first peak, from the power peak for arc reignition and droplet formation, second peak. One of the goals of this function is to reduce the power used in the process, shooting the power down between steps, which is the opposite of the standard process, where the power keeps high all the time and with longer power peaks.

Finally, the retractable wire feed applies an assistant wire feed motor, to give mechanical support to the process, pushing and pulling the wire when necessary, creating a synergic and optimized process (Kah et al., 2013). In this situation, the power peak to drop detachment is assisted by the wire pulling, where the surface tension is the main actor in drop detachment, instead of the power peak and electromagnetic pinch force. In some processes like *RWF 1*, the power peak is not used and the process has just the arc reopen peak. The reduction or disuse of power peaks acts to spend less power in the welding process and also give less heat to the melt pool.

3.2. Welding parametrization

Table 1 shows all the process variants tested and the parameters set in each machine for each process to reach the weld bead geometry wanted, as shown in Figure 1. Among them, the *ECP 3* had the limitation of 1 mm wire, which requested a significantly higher wire feed speed as shown. The wire feed speed shown is the one set in the machines and it was not measured with a separated device, therefore, big differences in the wire used by each process showed in Table 1 can be related with the machines miss control.

The first test with all the power sources was made using the same parameters: 4 m/min wire feed speed and no variation in voltage and arc dynamic factor. This wire quantity is very near to the amount necessary to produce the geometry wanted.

With this wire feed similarity, in the parametrization process the difference of geometry produced by each process was noticeable in the first test, which can be related with the goal of each one set by the producer. Processes like *ECP 1* and *ECP 2* almost achieve the geometry goal of 6 x 2,5 mm in the first test, showing a rounded, wet weld bead, being necessary just a few more tests to reach the geometry wanted. *RWF 3*, in turn, achieved the geometry sought in the first test. However, processes such as *SP 3* and *ECP 4* showed some difficulties in the parametrization process, with a too wet weld bead and parameter variations with more unpredictable behavior.

As shown in the Table 1, some processes had to have some extreme variations in relation with its range to reach the weld bead geometry wanted. This makes the results more ambiguous and have to be analyzed carefully. Even though the variants are in the same power range of GMAW, different results are generated.

Table 1 – Parameters set on the power sources to reach the weld bead geometry.

Process variation	Wire feed speed (m/min)	Voltage correction factor	Arc Dynamic factor
SP 1	4	-0,5	0
SP 2	3,7	-0,3	0
SP 3	3,7	-8	0
ECP 1	3,9	+0,4	0
ECP 2	3,81	-8	0
ECP 3	6	5	0
ECP 4	3,9	0	0
ECP 5	4,2	0	0
RWF 1	4	0	0
RWF 2	6	-6	10
RWF 3	4	0	0

Therefore, there are some processes that can be considered better for this application, nevertheless not as good for another. It can be exemplified by the literature, where processes like *RWF 1* and *RWF 3* are highly used for additive manufacture procedures due to their retractable wire technique, known by produce convex weld beads with low heat input (Kah et al., 2013). On other hand, processes like *SP 1* and *SP 2* are more used for high penetration applications due to their high power used. So, the process's judgment must be considered specifically for each kind of welding application.

The theoretical heat input of each process was calculated using the Equation (1) and (2) and is shown in Table 2, with *RWF 1*, *RWF 2* and *RWF 3* having the lowest heat input between all the eleven processes tested, consecutively.

The results of theoretical heat input shown by the electrical controlled processes were not the expected. *ECP 1* and *ECP 3* presented higher heat input numbers than *SP 2* and *SP 3*, two processes that have no power or wire control. Since *ECP 3* is limited to 1 mm wire, this range of power could be more than what it can perform in a stable form, being not able to control the power properly. *ECP 2*, on the other hand, had a theoretical heat input next to the ones presented by the retractable wire feed processes, proving an effective result using the electrical control. The heat input gap between *ECP 2* and the standard processes was up to 5% less and up to 10% less than the other electrical controlled processes. This can be related with the fast decrease of power after the arc reopen power peak, presented in Figure 4, keeping the average current low.

The variations focused on root welding, *ECP 4* and *ECP 5*, showed high theoretical heat input number, with *ECP 4* presenting the highest between all the processes. This was caused by the fusion rate of this process, which is lower than the wire feed speed and ends up by diving into the melt pool with the wire still solid. The power supply liberates a very high current to quickly melt the wire, which elevates the average current.

To analyze the effect that the power and work behavior causes in the weld bead, it was made a macrograph from each sample. From Figure 6 to Figure 16 are shown the macrographs made from all the short circuit variations tested. There can also be seen the measurements of width and height and the area of penetration, additional material and ratio.

Table 2 – Power and theoretical heat input calculation

Process variation	I_{av} (A)	V_{av} (V)	Power (W)	Heat input (J/mm)
SP 1	183,93	17,92	3296,03	395,50
SP 2	171,89	17,59	3023,55	362,81
SP 3	168,58	17,63	2972,07	356,63
ECP 1	177,89	17,93	3189,57	382,73
ECP 2	169,2	16,84	2849,33	341,90
ECP 3	178,2	18,31	3262,84	391,52
ECP 4	203,85	18,36	3742,69	449,10
ECP 5	191,05	17,19	3284,15	394,08
RWF 1	183,16	14,54	2663,15	319,56
RWF 2	180,26	14,98	2700,29	324,02
RWF 3	144,7	18,87	2730,49	327,64

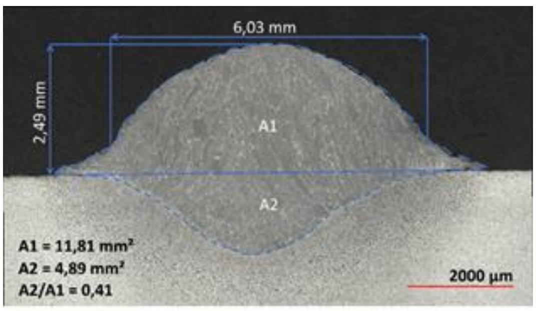

Figure 6 – SP 1 macrograph

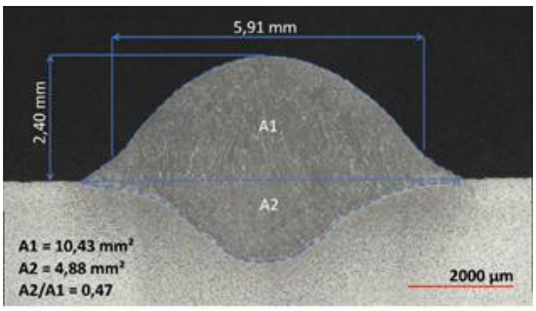

Figure 7 – SP 2 macrograph

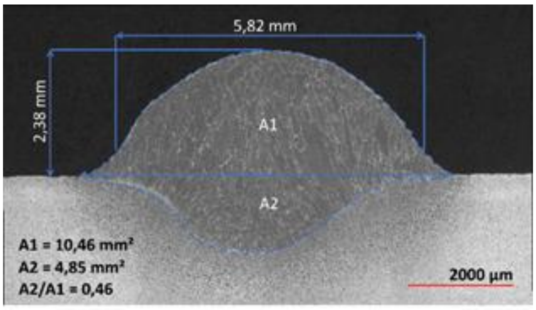

Figure 8 – SP 3 macrograph

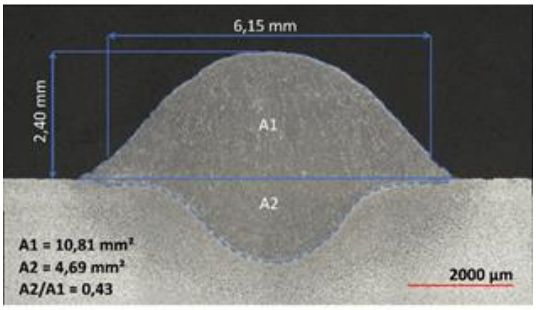

Figure 9 – ECP 1 macrograph

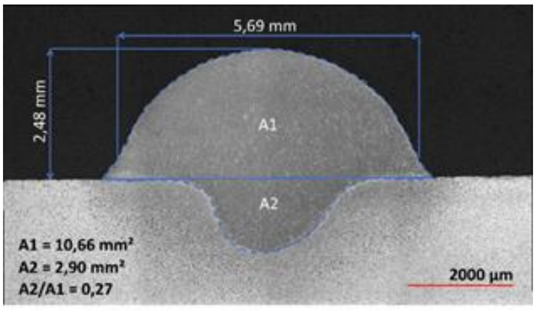

Figure 10 – ECP 2 macrograph

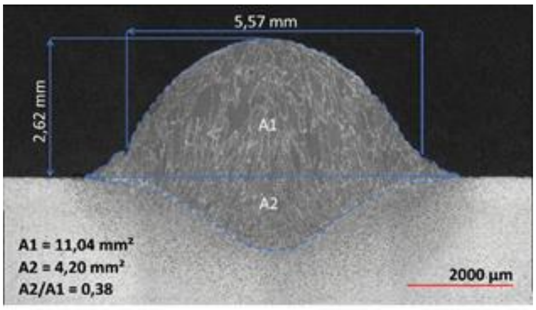

Figure 11 – ECP 3 macrograph

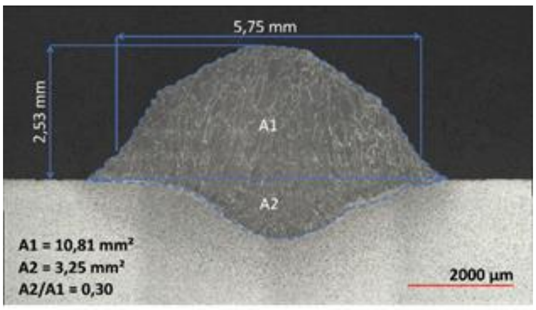

Figure 12 – ECP 4 macrograph

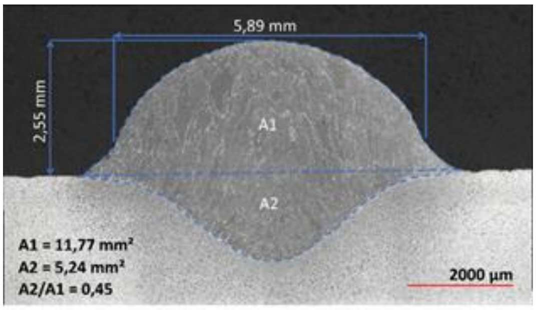

Figure 13 – ECP 5 macrograph

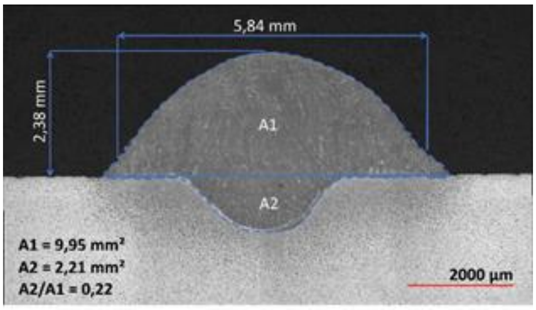

Figure 14 – RWF 1 macrograph

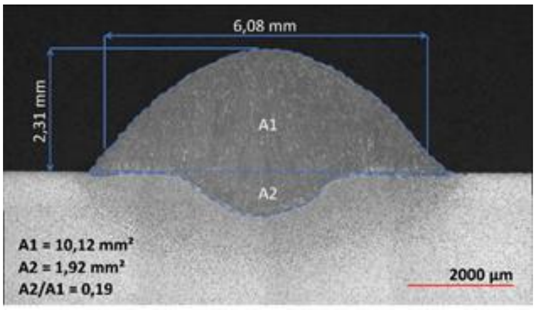

Figure 15 – RWF 2 macrograph

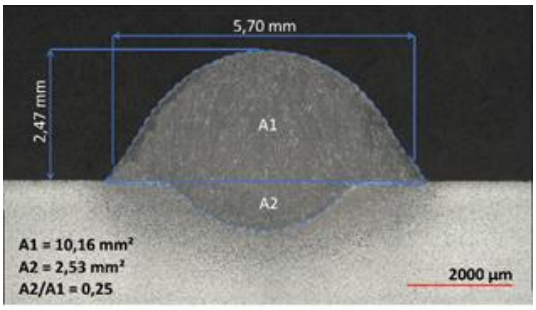

Figure 16 – RWF 3 macrograph

Among the macrographs, the biggest penetration was shown by *ECP 5* with 5,24 mm^2. As expected, the standard short circuit processes *SP 1*, *SP 2* and *SP 3* presented bigger penetration areas, with 4,89 mm^2, 4,88 mm^2 and 4,85 mm^2, consecutively. The electrical controlled processes presented better penetration control, however not as much as expected, with *ECP 1* and *ECP 3* producing penetration of 4,69 mm^2 and 4,20 mm^2, respectively. This can be linked with the theoretical heat input calculation, where the standard processes, in general, had a lower heat input number than the electrical controlled process, however not a smaller penetration. Therefore, the improvement of the process by the power control can be observed more in the physical field, not exclusively in the electrical calculation.

In Figure 17 regarding the *ECP 1* electrical oscillogram, it is possible to notice some key differences when compared with Figure 3, from *SP 2*. *ECP 1* presented more frequent drop detachment in the same time interval, which for the same amount of wire means smaller drops and less time of arc action. This acts to reduce the penetration, generating a colder drop and transferring less heat to the melt pool (Silva, 2005; Filho et al., 2013). Indeed, the power peak after detachment is longer, however the shot down after the peak is quicker. This can act to avoid the arc to continue the melting of the substrate, concentrating the power in the wire until the next detachment. The higher power peaks and lower current phase of the electrical controlled processes can be responsible for more power used, however, the smaller penetration can be seen as a result in the weld bead.

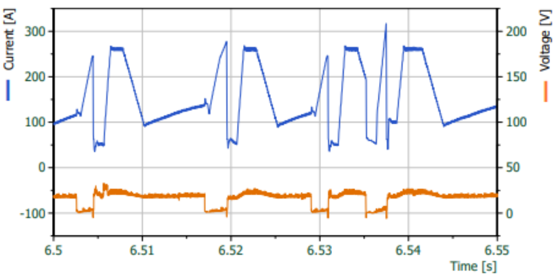

Figure 17 – ECP 1 electrical measurement / arc oscillograms

ECP 2 had a better performance in the penetration metric with 2,90 mm^2, putting this process next to the retractable wire feed performance, which ones presented 2,53 mm^2, 2,21 mm^2 and 1,92 mm^2 from *RWF 3*, *RWF 1* and *RWF 2*, respectively, being the three smallest and best results. These four processes were the only ones to present the expected result, unifying the theoretical heat input calculation with the physical weld bead numbers.

The process that occupied the middle field was *ECP 4* with 3,25 mm^2, the only one in the range of 3 mm^2. This result is the opposite of the expectations, since the theoretical heat input of this process was the higher one between the eleven tested. This links with the heterogenic behavior of wire melting and power used explained before. The punctual instabilities in this process generated by the wire melting rate make the average current higher, however, the average current out of these instabilities is next to the other processes, which leads to the result seen in Table 3 c).

4. Preview application on additive manufacture

To observe the difference that these processes make in an additive manufacture (AM) procedure, three of them were chosen to build a thin wall throughout AM. These processes were *ECP* 1, *RWF* 1 and *RWF* 3. The meaning of this choice is to show the practical difference between the application of a controlled short circuit process and a retractable wire feed process. Also, to show the comparison between two *RWT* processes from different brands developing the same task.

The results are presented in Figure 18, Figure 19 and Figure 20, regarding to the walls made by *ECP* 1, *RWF* 1 and 3, consecutively.

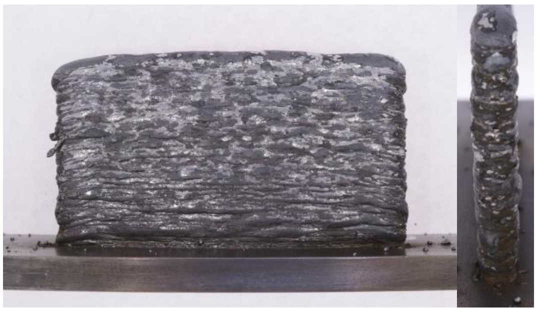

Figure 18 – Wall made with AM by ECP 1, front and side.

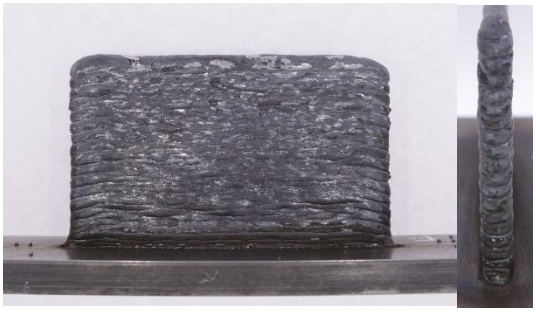

Figure 19 – Wall made with AM by RWF 1, front and side.

Figure 20 – Wall made with AM by RWF 3, front and side.

The difference in geometry is visible in the three samples. While *ECP* 1 produced a deformed and thicker wall, both *RWF* processes produced a continuous and homogeny wall. Therefore, the heat input range between the processes, even the controlled ones, are influential in the AM procedures, leading to visible changes in the results. As can be seen in the Figure 19 and 20, the layer division is better defined in the second wall, however this one has a concave top, what are the opposite than the showed by the wall made by RWF 1. Therefore, the method used by different brands to develop the retractable wire feed technique leads to differences in the final result as well.

Further studies on this AM procedure and its differences are being developed and will be commented on a separated article.

5. Conclusion

After testing all the processes listed, observing the physical results and also the calculus of heat input, it can be concluded that:

- The geometry adopted as a goal for the tests can influence the performance, since some processes are focused on developing welds with different goals and presenting limited variation possibilities;
- The retractable wire feed processes were effective controlling the heat input in the short circuit, significantly reducing the penetration compared with the standard processes. They present penetration areas up to 30% smaller and theoretical heat input up to 10% less than the average made by all the processes. Also, the power used was around 300 W less than the overall average, for the three retractable wire processes;
- *ECP 2* process had a performance next to the retractable wire feed processes even not using this technique, being an electrical controlled process;
- The electrically controlled processes, in general, did not show significant difference in the power used compared with the standard short circuits, some cases developing worse in these metrics;
- The theoretical heat input value alone cannot be used to predict the weld bead physical characteristics. The waveform can give a better idea of what to expect by the drop detachment frequency and high and low power phases behavior.
- Preliminary tests showed that the heat input and detachment differences have big influences in the additive manufacturing regarding to body geometries and process quality. Further works will specifically address this comparison, regarding thermal, geometric and metallographic differences.

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