COMPARISON OF GMAW SHORT CIRCUIT VARIATIONS APPLIED TO HEAT-INPUT AND GEOMETRY CONTROL IN THE ADDITIVE MANUFACTURE OF THIN WALLS

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Abstracts: *The ability to print complex 3D metal parts made the additive manufacture more present in the industry each year, reaching constantly new fields of applications. Between the processes capable of AM production, GMAW shows itself as the most common due to its characteristics of relatively easy operation, high productivity and low cost. However, the high heat input applied by this process becomes a challenge compared with others, impacting the part geometry, generating distortions, residual stress and affecting the mechanical properties of metals. Nevertheless, the production of short circuit variants with the goal of heat input reduction is studied by the welding companies, generating different methods of heat control. Therefore, three short circuit variants were used to develop an additive manufacture of a thin wall with ER70S-6 wire. The goals are to analyse their heat control and the impacts of each in the wall built. The weld bead geometry is chosen and reached with each process separatedly. The parameters used to make the weld beads are used again to built the walls and compare their performance doing the same task. The penetrations are analysed with macrographs and the temperature distribution during the AM process is measured by a thermal camera and compared. A hardness test is made to avaliate the mechanical characteristics imposed in the material and micrograph images to observe the grain formation. The results showed that the processes using retractable wire feed method can reduce the penetration in 50% compared with the process with power control and contiuous wire feeding. The comparison in the AM process showed difference between the geometries production, with the retractable wire processes generating a wall with more linear growth and thinner thickness. The electrically controlled process showed to have highest temperatures throughout the procedure and produced a deformed wall. The hardness tests and micrographs did not show significative differences between all processes.*

Key-words: *Additive manufacture, short circuit variants, temperature distribution, heat input.*

1. INTRODUCTION

Additive manufacture is becoming more and more presente in the industry due to its capability of produce parts with complex geometries that can not be made by machining. Being the principle of this process based on combining raw materials to create parts from a 3D model (17296-3:2014(E), 2014), AM can be produced by several processes, with the most comum of them in the industrial field being Directed Energy Deposition (DED) (Sing *et al.*, 2023). DED, focused on thermal energy to fuse metals while in deposition, includes the processes of Laser Additive Manufacture (LAM), Electron Beam Manufacturing (EBM) and the electric arc processes, Gas Tungsten Arc Welding (GTAW), Plasma Arc Welding (PAW) and Gas Metal Arc Welding (GMAW), included in the wire arc additive manufacture processes (WAAM). While LAM and EBM are known by its high precision, low heat input and low productivity (Karayel e Bozkurt, 2020), GMAW is known by its high productivity, having great capability of deposition and also low cost. This turns GMAW in the most used process in industrial AM procedures. Nevertheless, the high heat input applied in the part from this process becomes a challenge for geometry control, since this effect can induce residual stresses and part distortion (Feng, 2005; Nitschke-Pagel e Dilger, 2014). Therefore, companies from the wire arc field tryied to develop different methods to control this excessive heat coming from the short-circuit process, placing in low power range of GMAW (Kah, 2021; Kim e Chung, 2017; Norrish, 2006). This way, creating process variations with different characteristics and therefore different impacts in the additive manufactured part.

Joseph *et al.* (2005) tested and compared four different power sources for weld a V joint using pulse spray welding. It was used ER70S-6 wire and a shielding gas of 90% Argon and 10 % CO_2. It his work, he showed that, for the same base parameters, other parameters suffered big variations between power supplies, such as current power peak and drop detachment frequency, what impacted weld bead size and penetration. It was found a 17% gap of heat input between the smallest to the highest heat input, showing that, for different powersources, different results are expected. Henckell *et al.* (2020) studied the influence of the free wire length, distance between the contact tip and the wire tip, in the process heat input. It was observed that, the bigger is the free wire length, less heat is transfered for the workpiece, since the heat is dissipated in Joule effect in the wire length, melting it. This results in less energy in the electric arc and generate more convex weld beads, increasing the efficiency of the additive manufacture process. However, a big free wire length showed to be possible only in low welding speeds and, even in this situations, this practice generates spatter and arc instability, what leads to common weld bead deformations. On the other hand, the lowest the free wire length used, more stable was the arc behavior, spatter control and weld bead homogeneity. Yang *et al.* (2017) produced additive manufactured walls to investigate the influence of the cooling time between layers' deposition. Using colling pauses of 2, 5, 8 minutes, he observed that the temperature of the wall act like a curve and start to stabilize after the first minute, being the temperature difference between 2 and 8 minutes of pause of 30%, even being four times longer. However, the surface quality showed by the processes that used longer cooling pauses were considerably smother, presenting lower roughness. Therefore, as said by Yang *et al.* (2017), the cooling time of the process is a balance between quality and productivity. Liberini *et al*. (2017) e Kumar *et al.* (2021) discussed the microstructure difference throughout the wall additive manufactured. They noticed the presence of three different grain formations: a ferritic structure with bands of pearlite and finer grains in the first layers, caused by the thermal shock coming from the cold workpiece, what generates fast solidification. The middle zone, that is under effect of high temperatures for longer time, showed coarsed and equiaxed grains of ferrite and the upper zone presented lamellar bainitic structures, being this last zone the one that stays less time under heat input. Indeed, Kumar *et al.* (2021) considered the influence of shielding gas flow rate irrelevant for the weld bead geometry, althought not for heat input, appearance and control of spatter, pointing high concentrations of CO_2 as one responsible for defects like cracking and porosity.

Therefore, the present work focuses on analyse the impacts generated by different short circuit methods in an additive manufacture process using GMAW. This study is made using three short circuit variants and applying them to an additive manufacture of a thin wall. The wire material, welding speed, shielding gas and its flow are equal. The temperature distribution is measured and the theoretical heat input is calculated for each wall. In sequence, the walls are used to generate a hardness test profile and micrographs to analyse the microstructure of different points of the wall.

2. MATERIALS AND METHODS

2.1. Materials used

The GMAW additive manufacture were performed in a substrate of mild steel S235JR, cutted with 200 mm length, 20 mm width and having 8 mm of thickness. The wire was type ER70S-6 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. Equipment

The power sources and auxiliary equipments used are listed: EWM Alpha 552 with feeder drive 4X HP; Fronius TPS 400i, with a WF 25i Reel R wire feeder, SB 60i R splitbox; OTC Welbee P502L; 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 goal is to compare the performance of three different short circuit variations applied to an additive manufacture process. This three processes are: EWM ColdArc, Fronius CMT and OTC Synchrofeed. The meaning of the comparison is to observate the beahvior of two retractable wire feed processes, CMT and Synchrofeed, performing the same task. Also, use ColdArc, that is an electrical controlled process, to have a comparison between the perfotmance of temperature control from a retractable wire feed and an electrical controlled process, being this first known by having a better heat input control.

To produce this comparison, the same weld bead geometry was used for the three processes, which were parametrized to achieve a geometry of 6 mm width and 2.5 mm height, as shown in the Figure 1 a). These parameters were used to produce a wall additive manufactured with 100 mm lenght and 60 mm height, as shown in Figure 1 b).

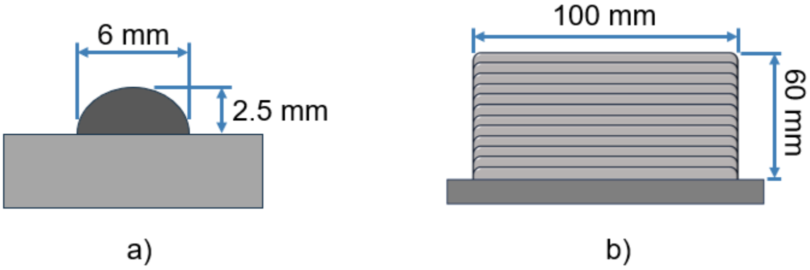


Figure 1. *Illustrations of: a) Weld bead geometry used for all the process variations; b) Wall additive manufactured.*

The welding procedure consists in fix the substrate in the table and use the robot equiped with the torch to move foreward when the arc is started. The robot moves in a 100 mm path and stop 60 seconds to cool the weld bead down, goes up in the value of the weld bead height and start the welding again, now in the opposite direction, overlapping the layers. For all the welds, it was used welding speed of 0.4 m/min and stickout of 10 mm. The process ends when the wall reaches 60 mm of height and it is made for all the three processes.

The welding procedure is assisted by a termal camera to observate the temperature distribution throughout the process. This can give a better comparison between the capability of termal control from each process variation. The measurement is made in four different areas equaly spaced and positioned in the wall growing direction as shown in Figure 2.

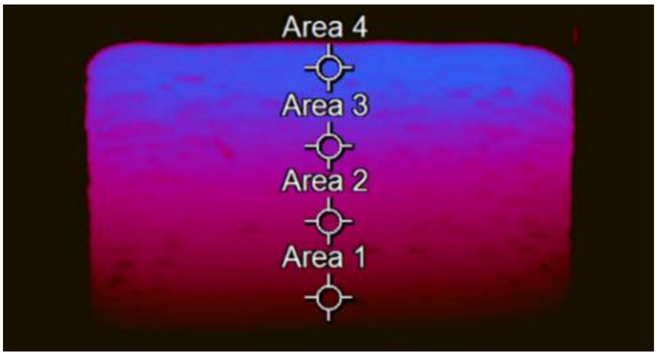


Figure 2. *Distribution of measurement areas throughout the wall.*

To observate the possible influences in the mechanical properties of the material applied by each process, it is performed a hardness test and micrographs with each sample. The hardness test is made longitudinally in the wall body, following the wall growing direction using HV1. It was made 125 points of measurement, spaced in 0.5 mm apart, with the last one calibrated to be 1 mm far from the top edge. Regarding to the micrographs, they were taken from four different areas: the heat-affected zone (HAZ), the bottom, middle and last layer. Both tests are exemplified in the illustration from Figure 3.

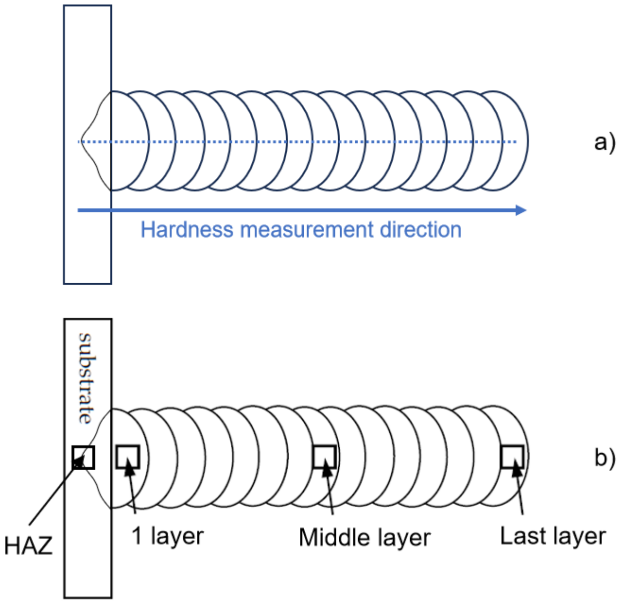


Figure 3. *Scheme of a) Hardness test and b) Micrographs areas.*

3. RESULTS

3.1. Parametrization and penetration

The three processes passed throught a parametrization phase to first reach the expected weld bead geometry, this way creating a base of comparation. The parameters set on the machines that produced the weld bead wanted are shown in Table 1. The numbers shown were the ones imputed in the welding machines, therefore, it was not used a separed device to measure the wire feed speed.

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

Welding power source	Process variation	Wire feed speed (m/min)	Voltage correction factor
EWM	ColdArc	3,9	+0,4
Fronius	CMT	4	0
OTC	Synchrofeed	4	0

The weld beads generated, representing the first layer of the wall, were used to produce a macrograph, this way allowing to compare the penetration of each process. The macrographs and oscillograms are showed in Figure 4, Figure 5 and Figure 6 for EWM ColdArc, Fronius CMT and OTC Synchrofeed, consecutively, showing the additive material area, penetration area and area ratio.

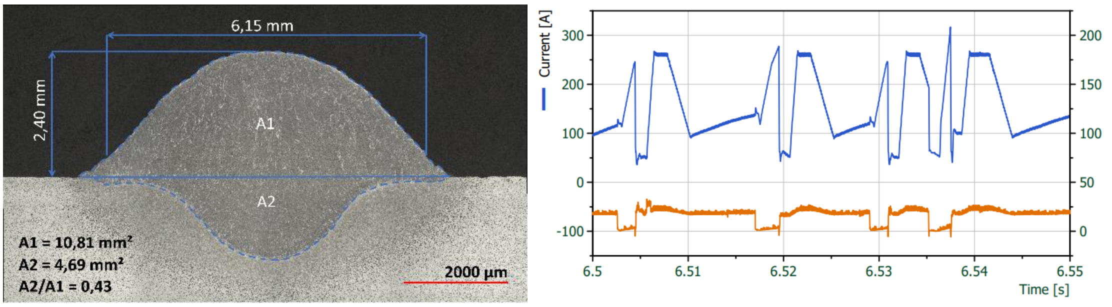


Figure 4. *Weld bead generated by EWM ColdArc and its welding oscillogram.*

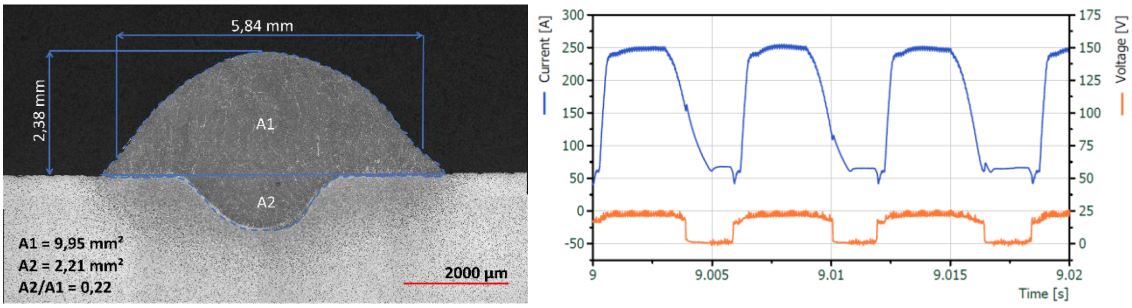


Figure 5. *Weld bead generated by Fronius CMT and its welding oscillogram.*

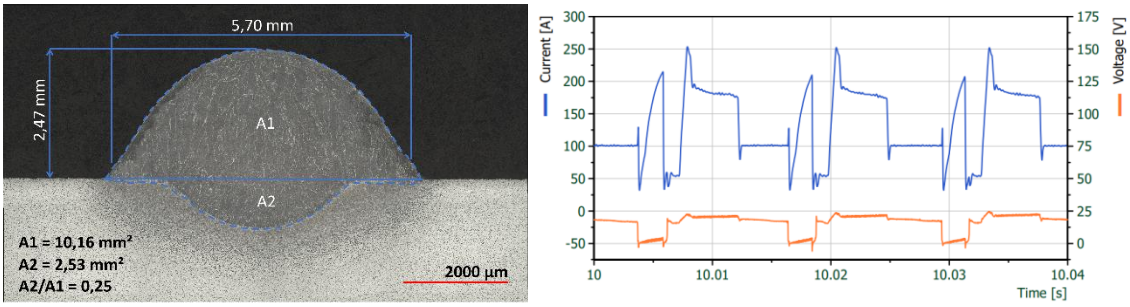


Figure 6. *Weld bead generated by OTC Synchrofeed and its welding oscillogram.*

It was notable that the retractable wire feed processes, CMT and Synchrofeed, had a more rounded weld bead, where it was not needed any variation to reach the weld bead geometry sought. ColdArc, in other hand, showed to be more wet and needed some parameter variations, however nothing extreme.

It can be noticed that the penetration in the weld bead generated by the retractable wire feed processes CMT and Synchrofeed is significantly smaller than the one made by ColdArc, presenting areas with 52% and 46% of reduction, consecutively. The weld bead made by CMT and Synchrofeed showed to be also more convex.

In the oscillograms it is possible to see the power control from each process. While ColdArc tries to control the drop detachment with the current modulation only, Synchrofeed and CMT unify the wire retracting with the power control steps, generating a mechanic process. It is shown in the oscillograms, having well defined and flawless drop detachments.

These characteristic have great inpacts in the AM process. The bigger penetration generates the overmelting of the previous layer made. This, united with a wet weld bead, decrease the potential of wall building. It causes the production of shorter layers and take more time and material to reach the height expected.

3.2 Additive manufacture

The walls built with these parameters are shown in Figure 7 a), Figure 7 b) and Figure 7 c), showing the front, side and top views, consecutivelly. All the walls have approximately 60 mm height in its center line.

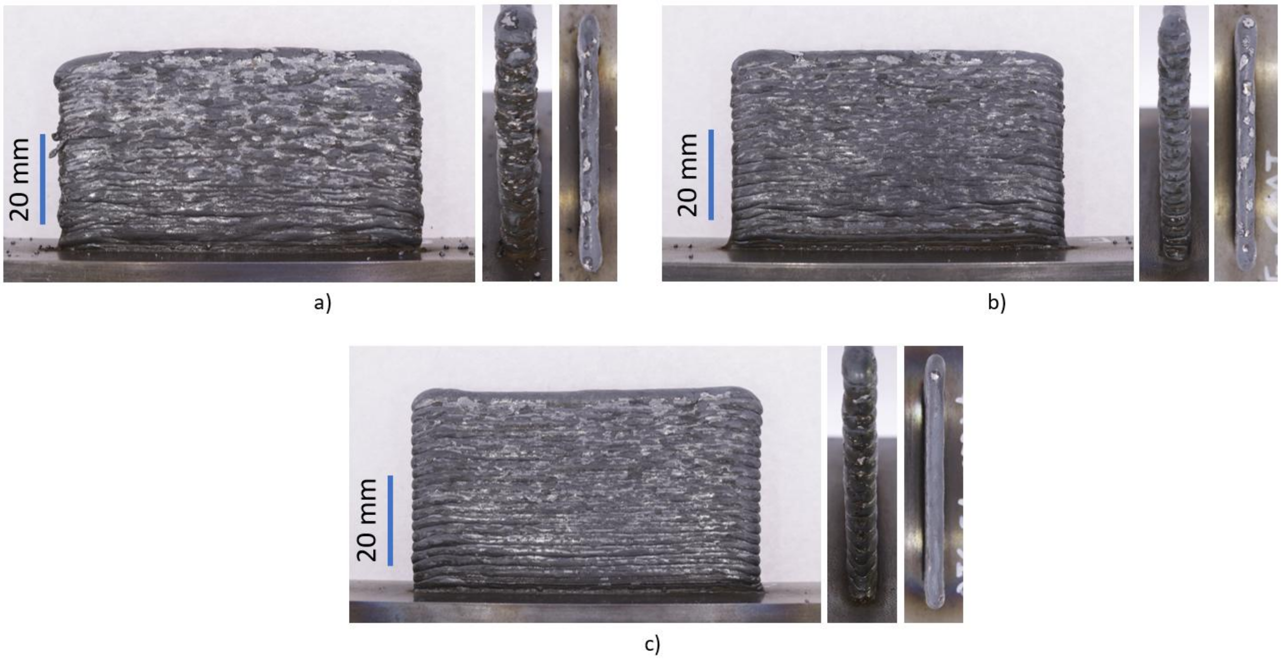


Figure 7. *Walls additive manufactured made by: a) EWM Cold Arc; b) Fronius CMT; c) OTC Synchrofeed.*

Between these three, ColdArc took more layers to finish the wall built, with 37 layers. It was the one that suffered more with surface distortion and weld bead oversized. Its layer divisions are not visible and the wall thickness showed to be bigger. It showed also more presence of silicate solidification, what, according to Derrien *et al.* (2021), can be caused for the voltage used, the oxidation potential of the shielding gas and the alloying elements in the wire. Since the gas and wire are the same, the use of voltage should be the causator of this silicate formation, since the higher voltage generates a bigger weld bead, what is more propense to make contact with oxygen from the atmosphere. Following, CMT and Synchrofeed took 34 and 36 layers to be built, respectively. Synchrofeed had the better visual result, with layers very well defined and also the less silicate formation, what can be seen in its last layer, presenting just one point of the phenomenon. CMT placed in the middle term between the three processes regarding to visual, where the deformation of the weld bead in the path line can be noticed in some points of the wall. With the help of the macrographs, showed in Figure 8, these characteristics become more visible. The three macrographs were made in the middle plane of the walls, were the height measurement was made.

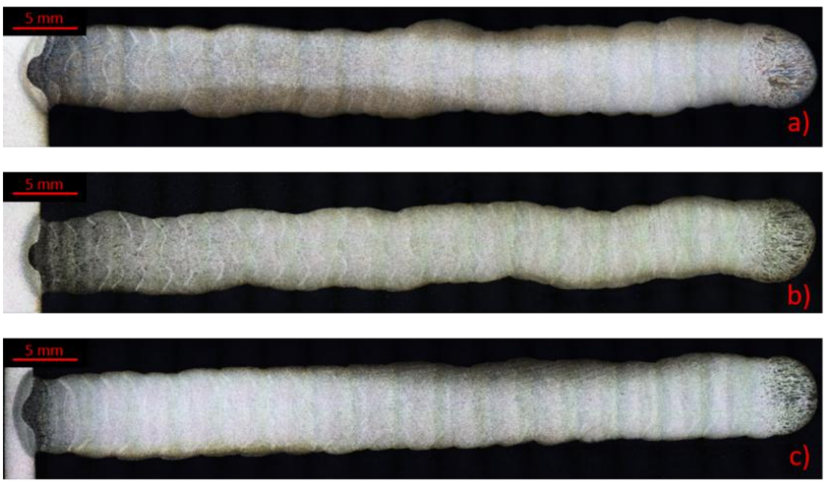


Figure 8. *Macrographs from the walls made by a) EWM ColdArc, b) Fronius CMT and c) OTC Synchrofeed.*

In the macrographs is possible to observate that CMT had the biggest changes in growth direction, changing it for both sides several times, not necessarily changing its thickness, what was maintained stable. ColdArc, in other hand, presented a vertical growth, however with random material accumulation in the sides, creating a randomly thickness. Synchrofeed showed the most stable process regarding to the wall construction. Its growth and thickness followed the same behavior in all the wall height, agreeing with the wall surfaces images. This thickness continuity and wall straight growing affect the AM process efficiency, which can be defined by the buy-to-fly ratio (Rasiya *et al.*, 2021), that is the relation between the mass of the part produced by the AM and the mass after the post-processing. In this metric, the thickness and wall direction changes means more time in post-processing with more material wasted, increasing the production costs of this application.

The nominal height from each wall, measured from the substrate top surface until the top of the wall in the center line, was 59.2 mm from ColdArc, 59.7 mm from CMT and 60.2 mm from Synchrofeed. CMT presented the biggest average layer height with 1.76 mm per layer, followed by Synchrofeed with 1.67 mm and ColdArc with 1.60 mm.

3.3. Termal camera analysis

The temperature in the wall body was observed during the wall constructions. In Figure 9, Figure 10 and Figure 11 is shown the temperature behavior in the four measuring areas for ColdArc, CMT and Synchrofeed, consecutively.

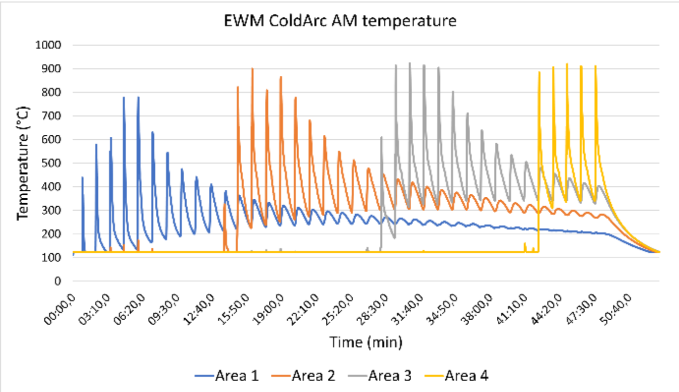


Figure 9. *Temperature behavior throughout the AM process from EWM ColdArc.*

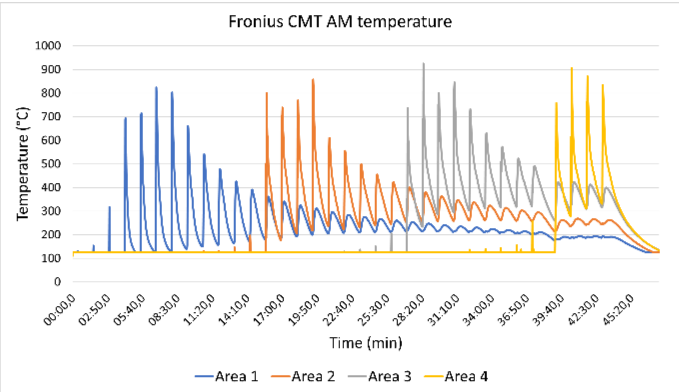


Figure 10. *Temperature behavior throughout the AM process from Fronius CMT.*

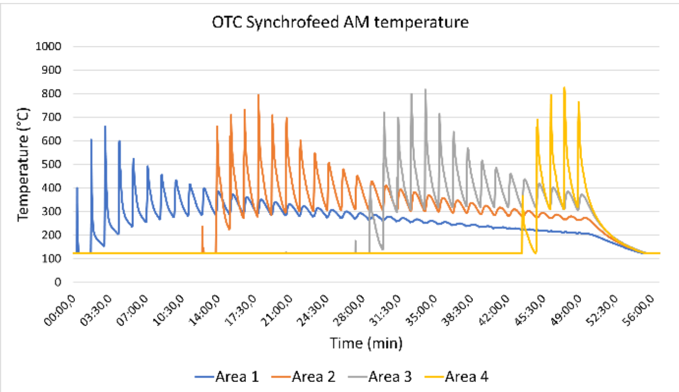


Figure 11. *Temperature behavior throughout the AM process from OTC Sychrofeed.*

The camera’s temperature range was 150ºC to 900ºC. ColdArc process reached the highest temperatures in all four measurement areas, reaching 900ºC in the 2º, 3º and 4º area, what can be related with the wall distortion, pointed as caused by the heat in the process (Feng, 2005). CMT reached this temperature only in the 3º and 4º area and Synchrofeed did not marked 900ºC, reaching 800ºC in 2º, 3º and 4º area. Therefore, Synchorfeed had the coldest temperature peaks between the three processes and the temperature range shown by them was quite large. The first area presented a temperature difference between the hottest to the coldest of 20% and 10% for the other areas. ColdArc and CMT did not showed a relevant difference in the first two areas, however in the two final ones ColdArc reached 900ºC in almost all depositions, while CMT kept next around 800ºC in the same areas.

CMT had the fastest temperature decreasement for the four areas in the time. Nevertheless, ColdArc and Synchrofeed showed a similar temperature decreasement, characterized by the bottom points of the temperature graphic. As can be seen in Synchrofeed thermal curves, the bottom temperatures were higher than the other two processes, keeping around 300ºC in all measuring areas. This behavior can be caused by the thermal conductivity of the wall, influenced by the wall thickness. According with the thermal conduction equation, the thermal conductivity is increased with the increasement of the body’s transversal area. Since this area in the wall made by ColdArc is considerably thicker, its body can dissipate heat more easily. Therefore, the heat control made by Synchrofeed is better dealing with the maximum temperatures, nevertheless there is an equilibrium with the heat inputed and the heat that the body is capable to dissipate. The literature shows some works that had some similar results, however using different heat inputs to bilt the walls, what can not be comparable with these, where the walls were made using the same weld bead.

3.4. Hardness and micrographs

To observe the diferences that each process causes in the mechanical properties of the material and the wall, the hardness test was made. In Figure 12, the hardness profile from the three walls is showed.

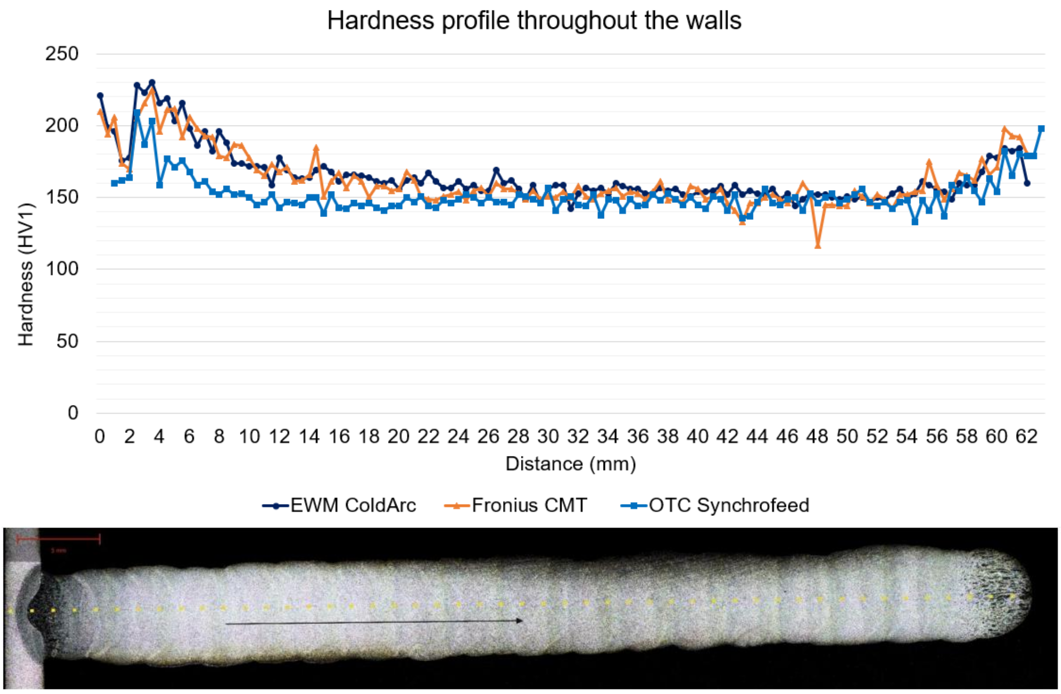


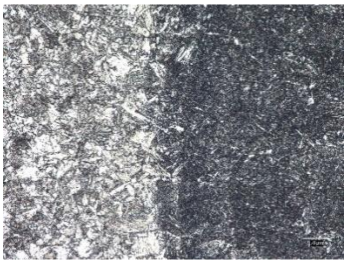
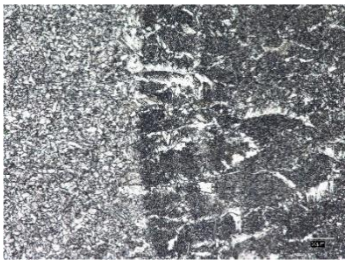
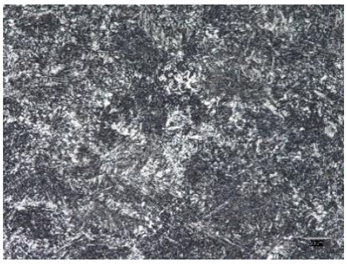
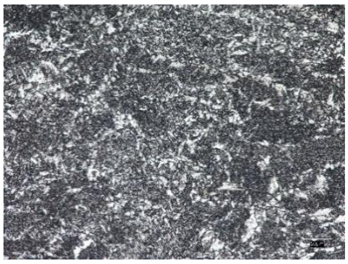
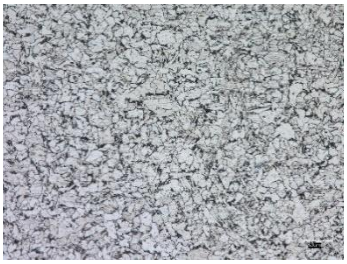
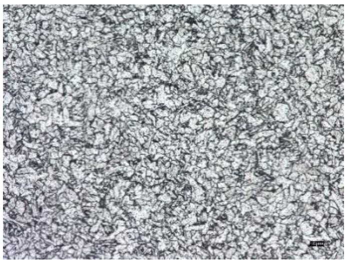
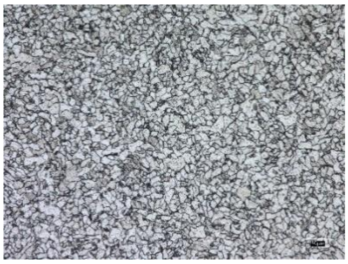
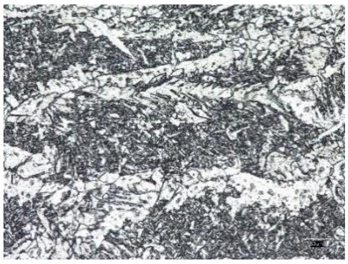
Figure 12. *Hardness test of the walls made by additive manufacture from three different processes.*

The HAZ is located between 2.5 and 3.5 mm, characterized by a hardness peak caused by a fine eutectic phase (Hirtler *et al.*, 2018). The hardness curves did not show significative difference for the three walls. However, the wall made by Synchrofeed showed a faster hardness decreasement than the other two, keeping 30 HV less between 4 and 12 mm. This can be related with the temperature difference pointed in the thermal graphics, where Synchrofeed process keept the bottom temperature high, allowing more the grain growth and decreasing the hadness (Napitupulu , 2017; Jr , 2001). This way, since the middle and top parts of the walls presented a similar behavior in the hardness test, the hardness changes could be caused not mostly by the temperature peak caused by the arc, although by the temperature decreasement during the process.

The hardness from the walls made by ColdArc, CMT and Synchrofeed stabilized in 25.5 mm, 18 mm and 6 mm, consecutively, placing in 29 mm, 21.5 mm and 10 mm in the graphic scale. The average hardness was 165 HV for the wall made by ColdArc, 163 HV from CMT and 152 HV from Synchrofeed, representing 8% of difference between extremes. Both retractable wire feed processes achieve a higher hardness in the last layer, with 180 HV from CMT and 198 HV from Synchrofeed, while ColdArc developed the same layer in 160 HV.

The four interesting points from the walls, placed in the thermal affected zone, first, middle and last layer where used to produce micrographs to observate the relation between the grains formed by each welding process and the mechanical changes. The micrographs are shown in the Table 2.

Table 2. *Micrographs of heat-affected zone, first, middle and lat layer from the walls.*

	EWM ColdArc	Fronius CMT	OTC Synchrofeed
HAZ			
First layer			
Middle layer			
Top layer			
		Table scale:	0.2 mm

In the TAZ, Synchrofeed presented the smaller grains and CMT the largest. However, after the fusion line, CMT presented the smaller grains, where is not possible to observate the edges, followed by Synchrofeed and ColdArc, having this last one an advanced grain formation. It can be seen that the middle layer from ColdArc have coarser grains with well defined edges. CMT and Synchrofeed presented very similar grain formation, being slightly more advanced in the first layer from the wall made by Synchrofeed. The porosity was notable in all the walls, with CMT presenting the biggest amount of it, followed by Synchrofeed and the smaller quantity of porosity made by ColdArc. All the wall bodies also presented lamellar structures in the last layer.

Liberini *et al.* (2017) e Kumar *et al.* (2021) presented similar results, where it was observated three principal grain formations also observed in this work. The presence of finner grains in the first layers can be related with the thermal shock coming from the cold substrate and, with this, fast solidification. The middle layers experience the higher gradient temperature, what causes the grain coalecense. Since the last layers do not experiment more heat, the grains have no excitation to generate the coalecense, presenting the alongated body in the solidification direction.

4. CONCLUSION

Analysing the results from the additive manufacture and mechanical tests, it could be observated that:

- Fronius CMT could control better the temperature of the process. CMT presented a middle control in the peak temperatures during the AM procedure compared with the others two processes. However, the temperature decreasement was faster throughout all the process.
- OTC Synchrofeed showed to be the most stable process in the wall bilt. The behavior was the same throughout the process and the geometry did not present significative changes. CMT had a heterogen growth that, different from ColdArc, that showed the same due to the melt pool with high temperatures and oversized, could have the heterogen growth due to arc changes during the AM process.
- EWM ColdArc could not bilt the wall that was aimed. The process showed the highest peak temperatures and suffered more with weld bead distortion, presenting deformed wall. As options to optimize this process in this application is give more time to cool down the wall in the AM process, reducing the average temperature and de overmelting, and changing the parameters throughout the wall bilt, reducing the power used in each layer, so reducing the melt pool size.
- The mechanical properties analysed in this work did not showed significative changes to be considered between the samples made. Further test as tension test could show more from the impacts from each process in the mechanical characteristics of the samples.

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6. RESPONSIBILITY NOTICE

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COMPARAÇÃO DE VARIANTES DE CURTO CIRCUITO GMAW APLICADOS NO CONTROLE DE APORTE TÉRMICO E GEOMETRIA NA MANUFATURA ADITIVA DE PAREDES FINAS

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Resumo: *A capacidade de imprimir peças metálicas complexas em 3D torna a manufatura aditiva mais presente na indústria a cada ano, atingindo constantemente novos campos de aplicações. Dentre os processos capazes de produzir MA, o GMAW mostra-se como o mais comum devido às suas caraterísticas de relativa facilidade de operação, alta produtividade e baixo custo. No entanto, o elevado aporte de calor aplicado por este processo torna-se um desafio em comparação com os demais, tendo impacto na geometria da peça, gerando distorções, tensões residuais e afectando as propriedades mecânicas do metal. No entanto, a produção de variantes de curto-circuito com o objetivo de reduzir o aporte de calor é estudada pelas empresas de soldagem, gerando diferentes métodos de controle do mesmo. Assim, foram utilizadas três variantes de curto-circuito para desenvolver manufatura aditiva de uma parede fina, utilizando arame ER70S-6. Os objectivos são analisar o controle térmico e os impactos de cada um na parede construída. A geometria do cordão de soldagem é escolhida e então obtida com cada processo separadamente. Os parâmetros usados para fazer os cordões são usados novamente para construir as paredes e comparar o seu desempenho desenvolvendo a mesma tarefa. As penetrações são analisadas com macrografias e a distribuição da temperatura durante o processo MA é medida por uma câmara térmica e comparada. É feito um teste de dureza para avaliar as caraterísticas mecânicas impostas ao material e imagens micrográficas para observar a formação de grãos. Os resultados mostraram que os processos que utilizam o método de alimentação de arame retrátil podem reduzir a penetração em 50% em comparação com o processo com controlo de potência e alimentação de arame contínuo. A comparação no processo MA mostrou diferenças entre a produção de geometrias, com os processos de arame retrátil gerando uma parede com crescimento mais linear e espessura mais fina. O processo controlado eletricamente mostrou ter temperaturas mais elevadas ao longo do processo e produziu uma parede deformada. Os testes de dureza e as micrografias não mostraram diferenças significativas entre todos os processos.*

Palavras chave: *Manufatura aditiva, variants de curto-circuito, distribuição de temperature, aporte térmico.*