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NUMERICAL SIMULATION OF THE THERMAL BEHAVIOR IN THE DEPOSITION OF A MULTILAYER WALL OF STEEL AISI 316 BY DED-PTA

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Abstract. *Structural projects necessitate understanding the mechanical properties of the material. However, this becomes challenging in metal additive manufacturing processes, where material is progressively deposited layer by layer to achieve the desired geometry, simultaneously manufacturing the material and the part. In such cases, the thermal cycles and material properties are dependent on each process, where the chosen processing parameters (deposition speed, powder feed rate, and deposition current) determine the thermal behavior during multilayer deposition, ultimately affecting the microstructure and mechanical properties. This ongoing research aims to explore the impact of processing parameters on the thermal characteristics experienced by AISI 316 steel during the unidirectional trajectory deposition of a multilayer wall. Numerical simulations are being employed in this research stage to establish correlations between the process variables and the thermal cycles experienced by the deposited material. Simulation results reveal that during the processing of the multilayer walls, each deposited layer heats a specific material volume, influenced by the processing parameters. However, as the steady state is reached, this volume remains constant and aligns with the growth of the wall height. An increase in electrical current directly affects the heated volume, while an increase in deposition speed and material flow reduces the volume of previously deposited material affected by the thermal cycle. These findings highlight the potential impact on the microstructure, subsequent post-processing heat treatments, and ultimately, the material properties achieved through AM.*

Keywords: *Additive manufacturing, Thermal behavior, Stainless steel, Simulation parameters.*

1. INTRODUCTION

Additive Manufacturing (AM) has gained increasing importance since the second half of the last century, offering a disruptive method of manufacturing that differs from conventional processes, where material is removed to produce a specific geometry. Unlike these traditional methods, AM employs the addition of material to create the desired geometries. This approach presents several advantages, including the reduction of design and production steps, elimination of the need for molds, the fabrication of customized geometries, topological optimization, and rapid prototyping. However, like any new technology, it brings forth challenges to be addressed, such as the control of the manufacturing environment (including the presence or absence of a controlled atmosphere), increased productivity, and understanding the thermal behavior during processing, which directly affects the mechanical properties of the final geometry. This latter aspect is the central theme of this work.

Currently, a wide range of equipment capable of fabricating parts through AM can be found, using various types of materials such as polymers, composites, ceramics, and metals. In the context of metal part printing, two techniques are constantly evolving: Powder Bed Fusion (PBF) and Direct Energy Deposition (DED) (Farias and Vilarinho, 2022). In this work, the focus will be on the DED technique, specifically on Plasma Transferred Arc-Deposition (PTA-DED). In this process, a metallic alloy in powder form is deposited onto a base and is melted by crossing an electric arc that forms the plasma. As the metallic alloy solidifies, it forms a metallurgical bond with the base material on which it was deposited. In PTA-DED, the main parameters influencing the characteristics of the deposited layer are: deposition current, powder feed rate and deposition speed. Since the thermal behavior during deposition is strongly affected by these parameters, the geometry of the processed component, its surface quality, physical and mechanical properties can vary considerably.

Exploring the impact of processing parameters on thermal characteristics, valuable information can be obtained for process control and improvement, contributing to the production of parts with superior and consistent mechanical properties.

This work aims to understand the thermal behavior during the deposition of a multi-layered structure of stainless steel 316 and investigate the impact of deposition current, deposition speed, and powder feed rate through numerical simulations. Due to the challenges in directly measuring temperature (De Azevedo et al., 2022), simulations can assist in identifying suitable parameter combinations, thus avoiding wastage of raw materials and experimentation time.

2. MATERIALS AND METHODS

This work is structured into two sections: Plasma Transferred Arc (PTA) deposition process and numerical simulations to investigate the thermal behavior.

The study of the PTA deposition process, exploring the variation of parameters, particularly the deposition current, powder feed rate, and deposition speed, aims to gather information for numerical simulation (layer thickness, temperatures, time etc.) and comprehend how these factors influence the deposition process, as well as the physical and mechanical properties of the geometry. Analyzing these variations also significantly contributes to the optimization of the additive manufacturing process.

Numerical simulations were conducted to investigate the thermal behavior during the deposition process. These simulations enable a more detailed analysis of temperature distributions throughout the process, providing crucial information about heat transfer and cooling rates. Such insights are fundamental for understanding the influence of deposition parameters on the thermal behavior during deposition.

Throughout the study, atomized AISI 316 stainless steel is used as deposition powder, with a particle size ranging between 60 and 180 micrometers. AISI 316 is well-known for its excellent corrosion resistance and weldability. Figure 1 presents the (a) thermal conductivity, (b) specific heat, and (c) density as functions of temperature. The pre wall or work piece (10 mm x 70 mm x 330 mm) used is also made from the same material.

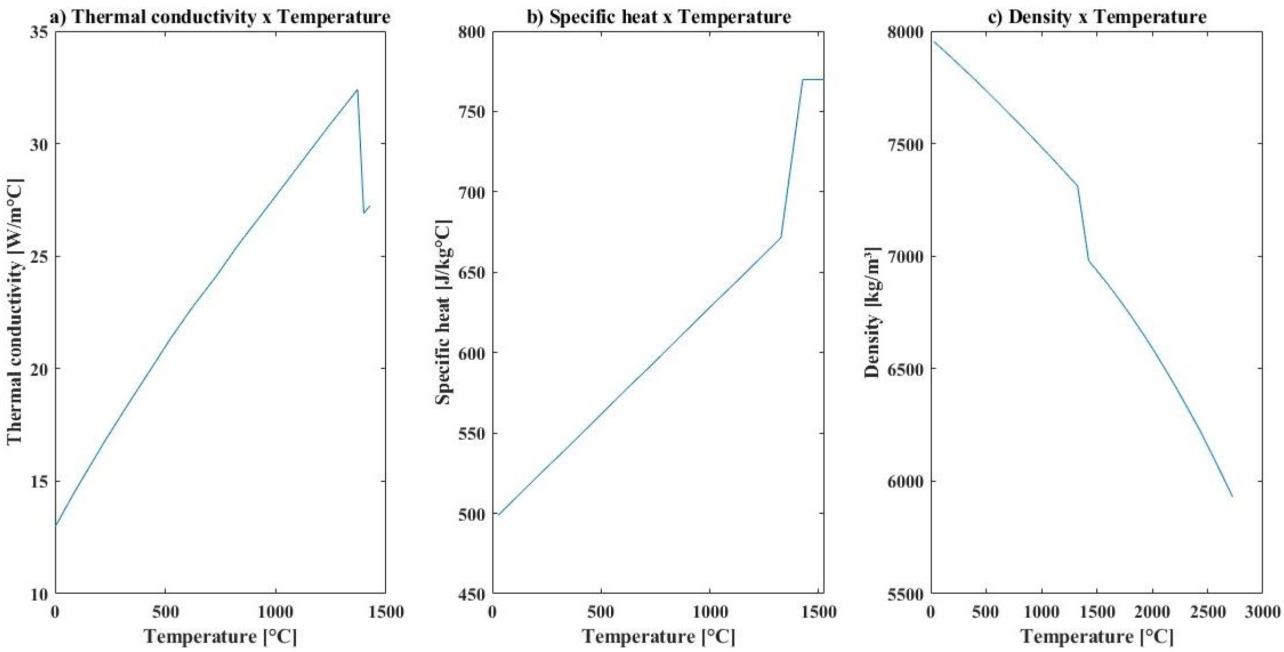

Figure 1. (a) Thermal conductivity, (b) specific heat, and (c) density, all as functions of temperature (Ansys student/23)

The alloy's melting point occurs at a temperature of 1398 °C (MT), which explains the abrupt changes in properties observed in Figure 1.

2.1 Processing

The PTA-DED deposition process, Figure 2, involves the controlled addition of molten material onto a melt pool on the base material or pre-deposited layer. Several parameters were evaluated to control the process, including deposition current (responsible for heat input and material fusion), powder feed rate (which determine the amount of material deposited on the base material melt pool), and deposition speed (which affect the deposited layer's thickness).

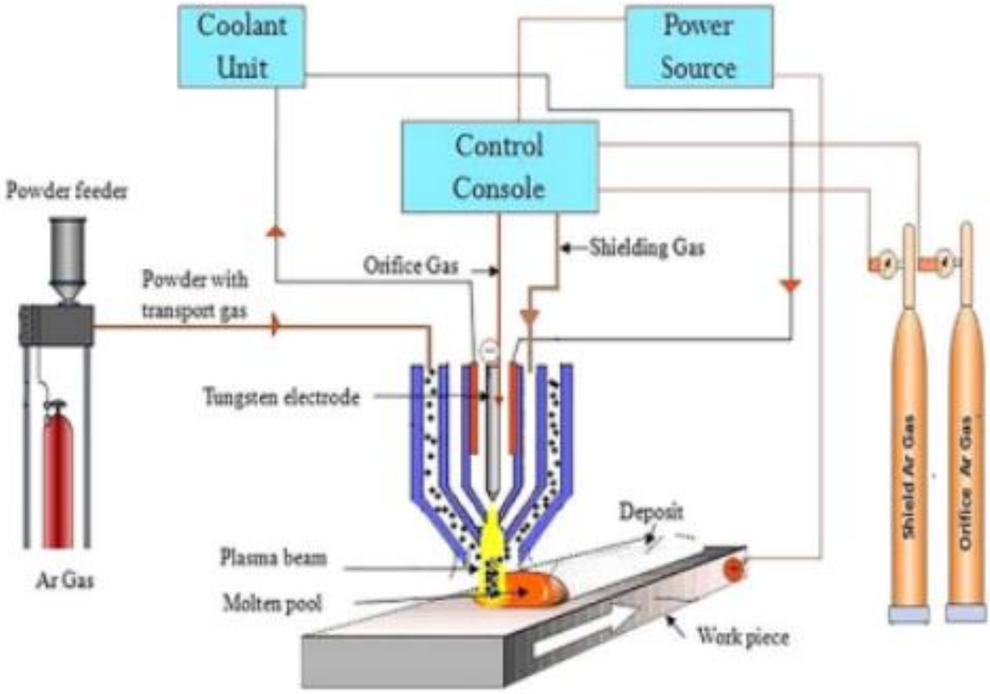

Figure 2 – PTA – DED Process - (Kumar et al., 2021)

The selection of these parameters is essential to obtain parts with desired properties and geometries. These applications include the repair of worn components, the production of protective coatings, and the construction of customized parts.

So far, the studies conducted in the laboratory have involved the deposition of linear multilayers with unidirectional deposition, varying the powder feed rate (25 g/min and 35 g/min), deposition current (100 A), and deposition speed (100 mm/min). The objective is to analyze the wall integrity and check the layer thickness for further enhancement of the numerical simulation model. The gas system used argon with flow rates of 0.8 l/min for shielding, 2.0 l/min for protection, and 15.0 l/min for the plasma. The interpass temperature of 150 °C was employed, measured at the center of each layer.

2.2 Numerical Simulation of Thermal Behavior

To simulate the thermal behavior, the Ansys software version 2022 R1 was used. The simulation considered a substrate with dimensions of 70 mm in height, 10 mm in width, and 330 mm in length, along with a deposited wall of 10 mm in width, 220.8 mm in height, and 330 mm in length. Each deposited layer has a thickness of 2.4 mm, and the ambient temperature was set at 22°C. The behavior of a wall with 92 layers was simulated. For the mesh, a linear approach was employed to avoid quadratic meshing and reduce the solution time. Figure 3 illustrates (a) schematic of the deposited wall and base material (pre-wall) and (b) the deposition process scheme.

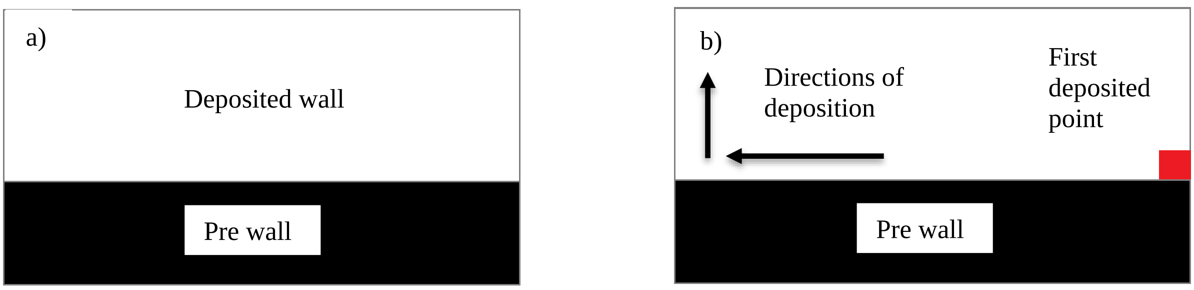

Figure 3 – Simulation scheme (a) wall and pre wall and (b) deposition process scheme

During the simulation, the properties listed in Table 1 were considered. To facilitate model convergence, some simplifications were adopted, such as using constant radiation and convection coefficients. Additionally, the deposited element was assumed to have a uniform temperature throughout its volume, and there was no phase change during the process. (Incropera, 2008).

Table 1. The thermal properties used in the simulation

Properties	Values	Units
Coefficient of radiation	0,8	W/mm² °C
Coefficient of convection	$4{,}41.10^{-6}$	W/mm² °C
Melting temperature (MT)	1398	°C
Ambient Temperature	22	°C

In the numerical simulation of the deposition process, the electric current was treated as a temperature variable, the material flow rate was linked to the deposited layer height, and the torch velocity was associated with the scanning speed. A total of four simulations were conducted, each with the parameters indicated in Table 2. These simulations were performed to investigate the effects of these parameters on the thermal behavior during the deposition process.

Table 2. Parameters used in the four simulations

Simulation	Deposition Temperature	Layer Height	Torch Travel Speed
1	T>>MT	2,4 mm	100 mm/min
2	T=MT	2,4 mm	100 mm/min
3	T= MT	1,2 mm	100 mm/min
4	T=MT	2,4 mm	200 mm/min

Each simulation allows determining the cooling time of each layer until it reaches the temperature of 150°C, measured at the central element, as illustrated in Figure 4(a), which is the interpass temperature. The temperature of the first deposited element, Figure 4(b), was also monitored throughout the deposition process.

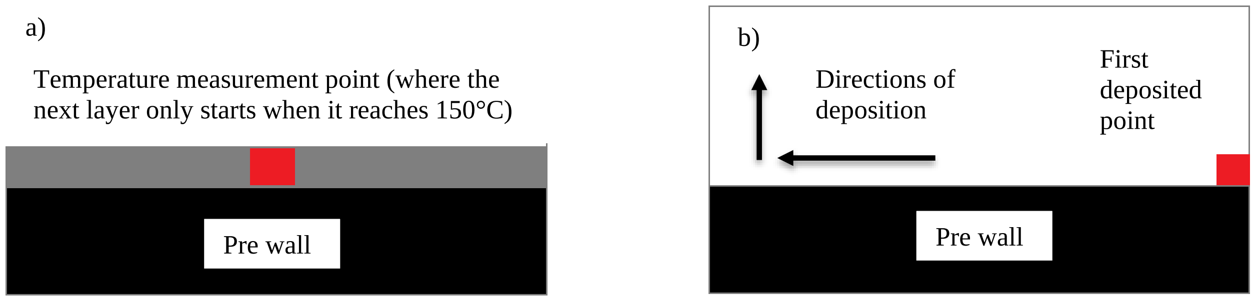

Figure 4 – (a) Temperature measurement element at each layer, and (b) first deposited element.

The simulations were conducted with a constant thickness, which was obtained from the best geometry observed in the experimental tests.

3. RESULTS AND DISCUSSIONS

Experimental results allowed the definition of some parameters used in numerical simulation, such as layer thickness. Figure 5 shows a five-layered-wall processed using 100 A deposition current, 25 g/min powder feed rate and 100 mm/min deposition speed; which resulted in a wall of approximately 12 mm height, with an average of thickness for each deposited layer of 2.4 mm, this is the value used in subsequent simulations. Depositions with a flow rate of 35 g/min ended up presenting a significant amount of unmelted material and, therefore, it was not taken into account in the simulation.

Figure 6 shows the thermal behavior during the deposition of the multilayers considering that the deposition temperature (2000 °C) is much higher than the AISI 316 steel melting temperature (1398 °C), 100 mm/min deposition speed and 25 g/min powder feed rate. It is evident that after entering steady state, which occurs around the 25th layer, the volume of material heated during each deposited wall is constant. This is extremely important because it indicates that, except for the last deposited layers, all previous ones must have the same mechanical properties, since they have gone through the same number of "thermal cycles".

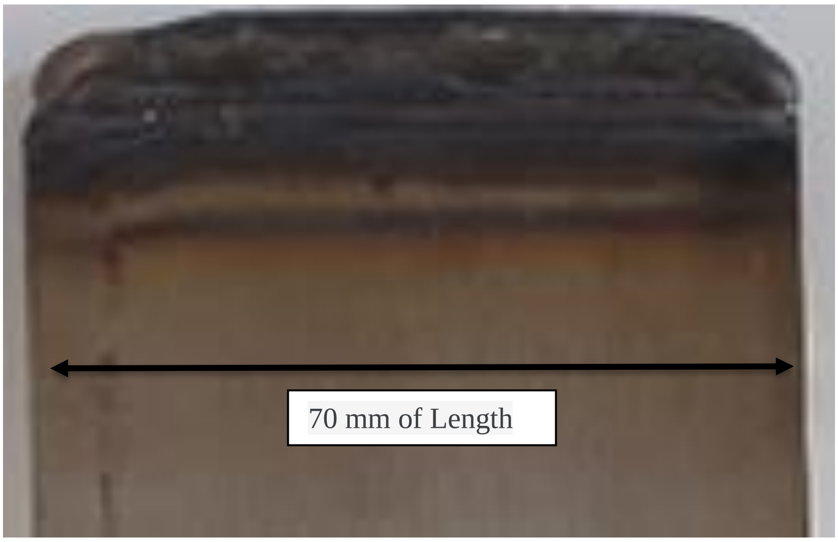

Figure 5 – A five-layered-wall processed by PTA-DED.

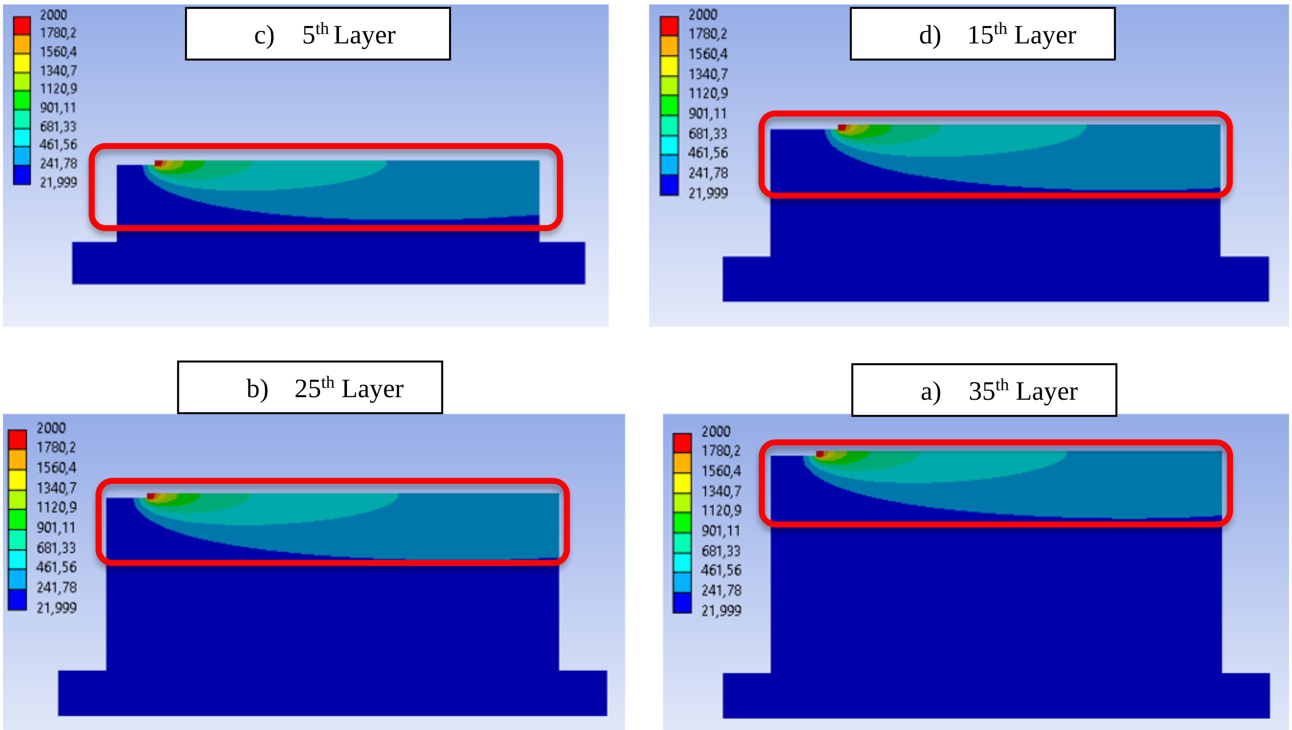

Figure 6 – Simulated thermal behavior during (a) 5th layer (b) 15th layer, (c) 25th layer and (b) 35th layer, the volume of material heated after entering steady state is constant.

In the simulation of the 92-layer wall deposition, the temperature decreases exponentially in the deposited elements. Increasing the deposition temperature in the simulation (corresponding to higher electric current in the experimental setup) causes the material to heat up more, expanding the heated volume (more layers in the steady-state condition) during each deposited layer. Higher temperature prevents lack of fusion (unmelted particles), but it also prolongs the cooling time (reducing productivity) and may cause the flow of molten material over the substrate's edge. On the other hand, increasing the deposition speed reduces the heat input (as the time the plasma stays in each specific location is reduced), reducing the heating of the already deposited walls (reducing the number of affected layers in the steady-state condition). Decreasing the powder feed rate results in walls with smaller thickness, facilitating cooling, but it leads to more layers affected in the steady-state condition, thus increasing the total build time due to the reduced thickness of each layer.

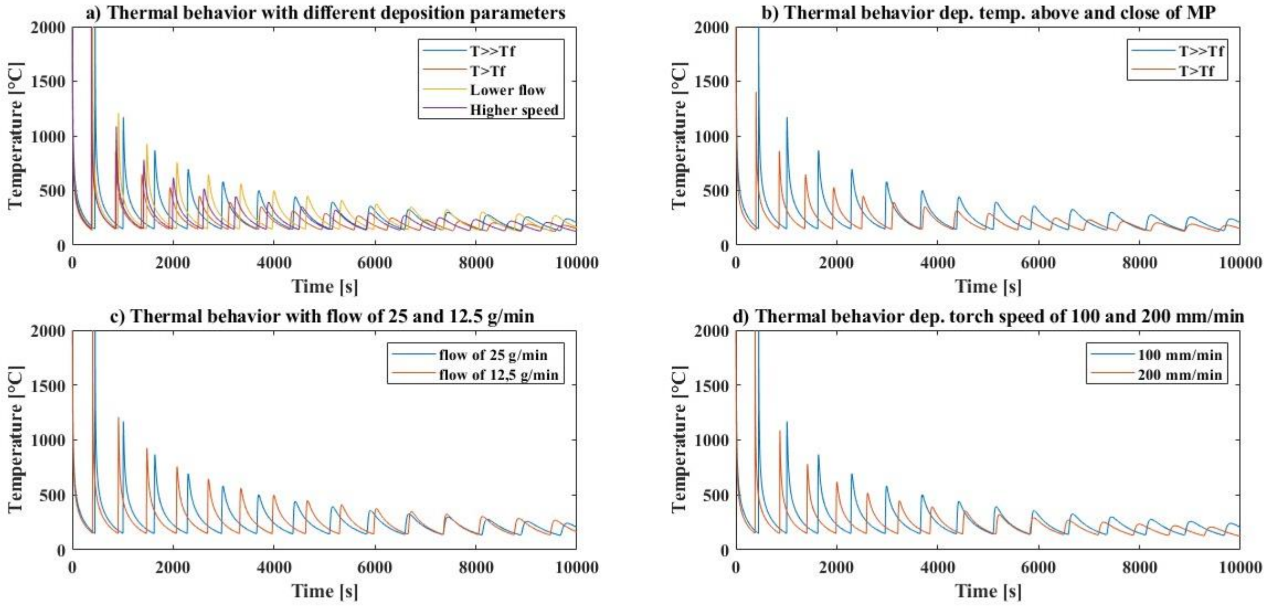

Figure 7 – Temperature in the first element deposited throughout the process depending on the different deposition parameters

In Figure 7, the temperature in the first element deposited in the first layer along the entire construction of the wall is highlighted, it is possible to see how the deposition parameters: deposition current (temperature in the simulation), powder feed rate and deposition speed affect the cooling curve and the number of layers required to enter a steady state. Factors such as a lower deposition current, a lower powder feed rate and a higher deposition speed make the cooling cycle faster. A lower deposition current decrease the maximum temperature peaks in the analyzed element.

Figure 8 presents the cooling time of the central element of each layer for different deposition temperatures, electric current and feed rate.

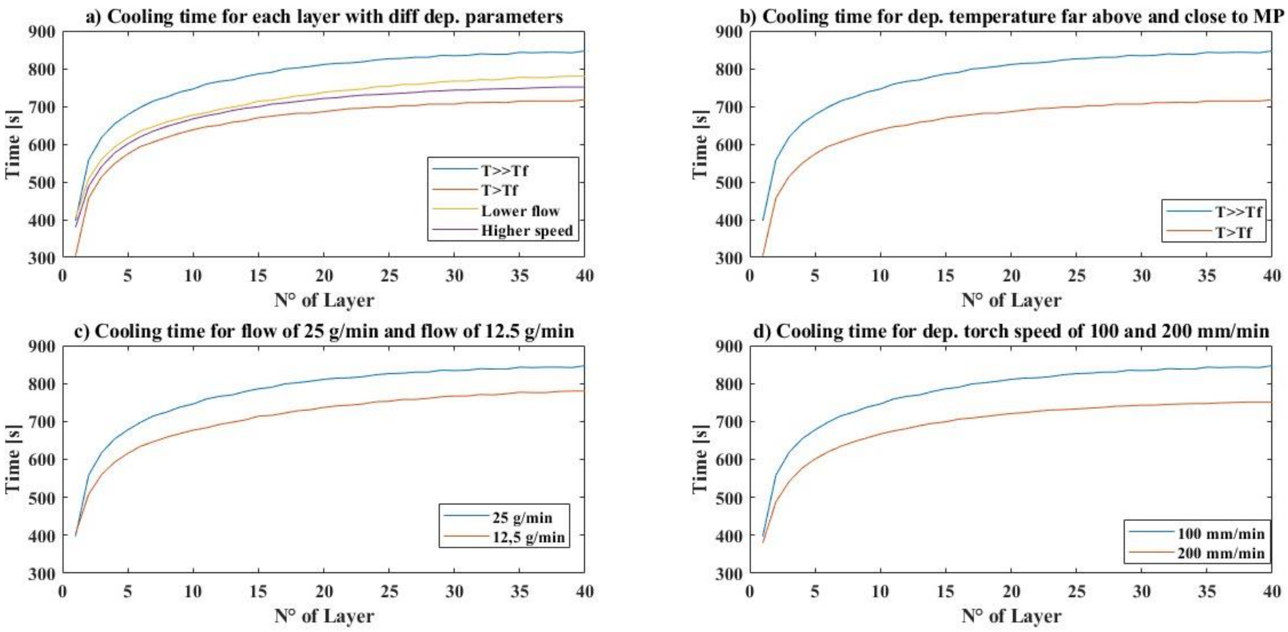

Figure 8 – Cooling time from deposition temperature up to 150 °C for the central element deposited in each layer for different processing parameters (lower deposition temperature, lower feed rate and higher torch speed)

The first layers have a shorter cooling time, because the base material is still at room temperature, facilitating the heat flow.

Among the four configurations analyzed, it was found that the deposition current, represented here as the deposition temperature, is the parameter that most affects the cooling time. Reducing the temperature (from 2000 °C to 1400 °C) results in a shorter cooling time, as the maximum temperature is lower, requiring a shorter time interval to reach the interpass temperature, which increases productivity (although care must be taken special measures must be taken to avoid lack of fusion).

Reducing the powder feed rate (from 25 g/min to 12.5 g/min) and increasing the deposition speed (from 100 mm/min to 200 mm/min) also reduces the cooling time. The decrease in the powder feed rate, reduces layer thickness in the numerical simulation, requires a greater number of layers to process the same geometry. The shorter cooling time occurs because the smaller layer thickness results in a smaller heated volume. On the other hand, the higher deposition speed, as mentioned earlier, reduces the time the plasma stays in the same location, thereby heating the already deposited walls less.

These adjustments demonstrate how altering the process parameters can impact the thermal behavior and cooling time, ultimately affecting the overall productivity and efficiency of the additive manufacturing process.

4. CONCLUSIONS

In this study of the behavior of the thermal cycle in multilayers deposited by PTA-DED, which used numerical simulation to understand the heat flow of linear walls with multilayers, it is possible to identify that the processing parameters (deposition current, powder feed rate and deposition speed) have an impact on the thermal cycle to which the material is exposed. During the deposition of multilayer walls it is possible to reach the permanent heat flow regime that describes the volume of material (amount of layers) that is affected by the deposition cycle, being this volume dependent on the deposition parameters.

Reducing the deposition current, the powder feed rate and increasing the deposition speed are approaches that can manipulate the cooling time and therefore better control the properties of the processed material. However, certain precautions must be observed in order not to compromise the manufactured part. Reducing the deposition current and increasing the deposition speed can result in lack of fusion, while decreasing the powder feed rate requires a greater number of layers, which can extend total build time.

5. REFERENCES

De Azevedo, A. M., Dos Santos Magalhães, E., & Da Silva, R. G. D., 2022. “A comparison between nonlinear and constant thermal properties approaches to estimate the temperature in LASER welding simulation”. Case Studies in Thermal Engineering, Vol. 35, p. 102135.

Farias, R. M., & Vilarinho, L. O., 2022. “Computational Simulations of Metal Additive Manufacturing Processes: An Introductory Review”. Soldagem & Inspeção, Vol. 27.

Incropera, F. P., 2008. “Fundamentos de Transferência de Calor e Massa”. 6° Edição ed. [s.l.] LTC.

Kumar, P., Sawant, M. S., & Jain, N. K., 2021. “Optimization of process parameters in micro-plasma transferred arc deposition process for cobalt-based alloy”. Materials Today: Proceedings, Vol. 44, p. 1681-1686.

6. RESPONSIBILITY NOTICE

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