

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Thermal Modelling of the Laser-Powder Bed Fusion process, a numerical and experimental work

João Manuel Santiago de Almeida Gomes



Mechanical Engineering M.Sc.

Supervisor: Prof. Marco Parente

Supervisor: Prof. Jesper Hattel

Co-Supervisor: Prof. Mohamad Bayat

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Abstract

Metal additive manufacturing (MAM) has experienced tremendous growth because of its enhanced production capabilities and the innovative design concepts it enables. Additive manufacturing (AM) has progressed from rapid prototyping for product development to the production of structurally challenging components. Consequently, the requirement for numerical models that provide reliable estimates of a component's microstructure, distortion, and residual stresses has increased. Due to the multi-physics character of MAM, it is still difficult to predict temperatures and stresses during production, necessitating multiple experimental tests or numerical simulations to obtain the appropriate components.

This project involves the development of a computationally efficient part-scale thermal model to reliably predict temperatures generated during Laser Powder Bed Fusion (L-PBF) of Ti-6Al-4V Titanium alloy. The thermal model is produced in the commercial CAE software ABAQUS through a developed Python script that partitions the geometry as desired and defines loads, boundaries, mesh, and initial conditions according to the Flash Heating (FH) method. Subsequently, the model is calibrated through comparisons with thermocouples *in-situ* recordings extracted during production.

Furthermore, after obtaining a well-behaving model, reliability tests on the thermal model are executed in order to understand the model's performance. The analyses go through boundary condition changes, the number of layers lumped, and the overhang effect on the temperature distribution during the manufacturing process. The studies demonstrate the impact of heat accumulation on the overhangs and prove that lumping layers significantly impact computational performance. From one layer lumped to sixteen layers, we go from 117 hours to 18 hours of simulation.

Lastly, a MATLAB code was created to extract and process simulation data for later analysis with *in-situ* measurements taken during the experimental process with photo-sensors, where it was possible to observe cold and hotspots.

Keywords: Metal additive manufacturing, Numerical modeling, Flash heating method, Thermal simulations

Resumo

O fabrico aditivo de metais (MAM) sofreu um enorme crescimento devido às suas capacidades de produção otimizadas e aos conceitos de design inovadores que permite. O fabrico de aditivos (AM) progrediu desde a prototipagem rápida para desenvolvimento de produto até à produção de componentes estruturalmente desafiantes. Consequentemente, a exigência de modelos numéricos que forneçam estimativas fiáveis da microestrutura, distorção e tensões residuais de um componente aumentou. Devido ao carácter multi-físico do MAM, continua difícil prever temperaturas e tensões durante a produção, sendo necessário múltiplos testes experimentais ou simulações numéricas para obter os componentes esperados.

Este projecto envolveu o desenvolvimento de um modelo part-scale térmico computacionalmente eficiente para prever com algum grau de confiança as temperaturas geradas durante o Laser Powder Bed fusion (L-PBF) da liga de Titânio Ti-6Al-4V. O modelo térmico é construído no software comercial CAE ABAQUS através do desenvolvimento de um script Python que divide a geometria conforme desejado e define cargas térmicas, condições fronteira, malha, e condições iniciais de acordo com o método de Flash Heating (FH). Subsequentemente, o modelo é calibrado através de comparações com resultados gerados por termopares *in-situ* durante a produção.

Além disso, após a obtenção de um modelo bem comportado, são executados testes de fiabilidade no modelo térmico, a fim de compreender o desempenho do modelo. As análises passam por alterações das condições de fronteira, o número de camadas agrupadas, e o efeito de um overhang na distribuição da temperatura ao longo do processo de fabrico. Os testes demonstram o impacto da acumulação de calor com as sobreposição de camadas e mostram que o agrupamento de camadas durante a simulação tem um impacto significativo no desempenho computacional. De uma camada agrupada a dezasseis camadas, passamos de 117 horas para 18 horas de simulação.

Por fim, foi criado um código MATLAB para extrair e processar dados de simulação para análise posterior com medições *in-situ* realizadas durante o processo experimental com foto-sensores, sendo possível a identificação de coldspots e de hotspots.

Keywords: Fabrico aditivo de metais, Modelação numérica, Método de Flash Heating, Simulações térmicas

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João Manuel Santiago de Almeida Gomes

*“A ship is safe in harbor,
but that’s not what ships are for.”*

William G.T. Shedd

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Abbreviations

AM	Additive Manufacturing
MAM	Metal Additive Manufacturing
PBF	Powder Bed Fusion
DED	Direct Energy Deposition
CAD	Computer Aided Design
STL	Standart Tessellation Language
ASTM	American Society for Testing and Materials
BJT	Binder Jetting
SHL	Sheet Lamination
VPP	Vat Photopolymerization
MJT	Material Jetting
MEX	Material Extrusion
LOM	Laminated Object Manufacturing
SLA	Stereolithography
DLP	Direct Light Processing
UV	Ultra Violet
SLM	Selective Laser Melting
EBM	Electron Beam Melting
SLS	Selective Laser Sintering
FH	Flash Heating
SFH	Sequencial Flash Heating
GH	Gradual Heating
LPBF	Laser Powder Bed Fusion
EBPBF	Electron Beam Powder Bed Fusion
DED	Direct Energy Deposition
HAZ	Heat-Affected Zone
TO	Topology Optimization
FEM	Finite Element Method
FE	Finite Element
LAM	Laser Additive Manufacturing
UAS	Unmanned Aerial System
KMC	Kinetic Monte Carlo

Chapter 1

Introduction

1.1 Project's Framework and Motivation

Since its original creation, Metallic Additive Manufacturing has experienced a significant increase in popularity. The ability to produce parts with almost no geometrical limitations is unmatched, especially with numerical methods such as topology optimization that generate structures based on specified objective functions. These technologies can considerably reduce the component's bulk dimension while keeping its structural integrity, as being able of developing exceedingly complicated shapes that no other manufacturing procedure could easily reproduce. In addition, a number of materials that were previously excluded due to their high hardness and, consequently, low machinability were included in the new production procedure that disregards these constraints, even though post-processing techniques are often applied. Meanwhile, in AM, novel materials like Titanium alloys with their high tensile strength-to-weight ratio are frequently employed [1, 2, 3].

Although AM technologies have other advantages beyond geometrical flexibility, such as reduced design cycle times and the need for little human interaction throughout the process, it is challenging to predict the results since the process is both highly transient and possesses localised physics (micro and meso scale) [4, 5].

This typical AM thermal behavior introduces defects that must be accounted for: excessive surface roughness, dimensional imprecision due to the heat cycles during layer deposition, microstructural defects due to the part's interaction with the surrounding atmosphere and rapid cooling, and residual stresses that arise from plastic deformation induced by localized material expansion and contraction between layers [6].

With the rise in the popularity of additive manufacturing and the increasing use of AM-produced parts in structural applications, new modeling and simulation approaches are required for process and performance representation. A strong link between discovery and validation experiments is more crucial than ever [5].

In addition, understanding the phenomena during SLM is more significant than evaluating the effect of process parameters. Under two distinct situations of inadequate and excessive heat input,

L-PBF may develop voids or internal porosities. In particular, the former state results of an absence of fusion while the latter is in keyhole-induced holes [2, 7]. *Ex-situ* and *in-situ* examinations are two methods for finding various sorts of porosities. The *ex-situ* research would provide inadequate information regarding how pores are created and hence would not identify the processes responsible for developing these spaces. Moreover, *in-situ* monitoring devices are sometimes prohibitively costly and might pose health risks to operators; hence, they cannot be utilized regularly to observe these physical events [7]. In addition, online monitoring necessitates a series of complicated preparations and calibrations beforehand, significantly increasing the entire analysis time. In addition, these online solutions frequently generate a considerable output data that is challenging to handle and store. Moreover, the coexistence of numerous interactive phenomena, such as recoil pressure, the Marangoni effect, evaporation, laser reflection, etc., all occurring within microns and microseconds, makes it exceedingly difficult to study the keyhole and its subsequent pore formation mechanism through experimentation alone [7].

Therefore, this thesis' motivation is to create a well-behaving model that can capture most of the thermal behavior of an L-PBF process by using experimental data to calibrate and afterward test its reliability. When validated with experimental results, it will allow to test different parameters without the cost of producing a piece based on a trial-and-error method to detect defect formation.

1.2 DTU - Technical University of Denmark

The research presented in this thesis was developed over five months in collaboration with the Technical University of Denmark (DTU) in Lyngby, a very active and innovative European university. The internship was conducted face-to-face, specifically at the Section of Manufacturing, Department of Mechanical Engineering, on an Erasmus+ Traineeship agreement. Here, it is possible to find pilot productions with additive manufacturing techniques. Furthermore, performing high-tier research is achieved via experimental work and numerical simulation.

1.3 Objectives

The main goal of this dissertation is to obtain well-behaving thermal modeling of L-PBF that could be used to perform parameter studies. Another application of the developed work is a generation of a digital twin with *in-situ* measurements, or also the application of this method to solve the thermal component of a Weakly-coupled thermomechanical model. In order to achieve the main goal, in the beginning, the existing literature on numerical calculation in parts produced by AM, process parameters, and AM phenomena is analyzed. A comparison with experimental data is also conducted for multiple scenarios, where a numerical model was created to achieve similar results. Subsequently, training was undertaken in the FEM commercial software ABAQUS, used to perform thermal simulations. While doing so, further knowledge was sought in the literature related to the manufacturing process, modeling techniques, and defects during production. In the

end, a thermal model at part-scale for predicting the temperature field during the Laser Powder Bed Fusion was developed. This model was validated with *in-situ* thermal experiments and with a mathematical code developed, to analyze and process the *in-situ* measurements, taken during the process, with photo-sensors.

The work performed during the thesis allowed the creation of a scientific article to be submitted to an international journal regarding the numerical work.

1.4 Method followed in the project

The methodology can be found in greater detail in Chapter 3. An experiment with a specimen with an overhang is done, and *in-situ* measurements are taken with it. Afterwards, numerical modeling is developed, where the experimental data is used to calibrate the model. After achieving a well-behaving model, physical tests are performed as well as process parameters analysis in order to prove the reliability of the model.

1.5 Summary

In this Section, the contents of the remaining Chapters of this document are summarised:

- **Chapter 2 - Literature Review** - This chapter is focused on exploring the principles required to comprehend the developed work, such as additive manufacturing and the numerical modeling method;
- **Chapter 3 - Methodology** - The experimental setup, the numerical modeling, and the finite element method are presented and discussed with greater care.
- **Chapter 4 - Results and Discussion** - The numerical solutions to the simulations presented in the previous chapter are detailed, and the respective discussion is carried out.
- **Chapter 5 - Conclusion** - Final remarks on the developed work and possible future works that enhance the knowledge of additive manufacturing simulation are presented.
- **Appendix A** - No overhang geometry - The first approach
- **Appendix B** - Manuscript under preparation to be submitted to an international journal

Chapter 2

Literature Review

This chapter intends to introduce the reader to appropriate information about the relevant technologies and topics applied in this thesis. The chapter includes an introduction to the concept of Additive Manufacturing. Metal AM processes are deeply explored, as they are the main focus of this thesis. Applications of AM in various industries are also presented in this chapter. This is followed by an introduction to the different AM simulation methods and properties.

2.1 Additive Manufacturing

2.1.1 Definition

AM is defined as the process of building a part or a component directly from a solid model that involves a technique of fusing materials using a heat source and added material. The process involves slicing the model of the part into several layers, creating a toolpath that traces each layer, and then building the part layer by layer using filler material in a computer-controlled automated machine [8].

Since the process relies on adding material in each layer to form the final part geometry, it is called an additive process. In contrast, conventional machining processes start with a block of material and then employ material removal techniques to produce the final part geometry, hence the term subtractive process [8].

Although the terms 3D printing and AM are often used interchangeably, 3D printing is actually a subset of AM that uses the techniques described above to build parts from scratch. However, AM includes technologies such as 3D printing but also the addition of material to existing parts or assemblies for repair, refurbishment, or performance enhancement. Additionally, it offers greater design freedom and the ability to produce geometries that are not feasible with conventional manufacturing [8].

Possibilities include parts with complex internal channels, lattice, or honeycomb structures in order to save weight. The complex geometries or the overhang surfaces must be maintained with support material [9].

Details can be changed at the last minute as no dedicated forming tools exist. Additionally, additive manufacturing can eliminate a lot of assembly work, as a part assembled from many smaller components can be changed to a single piece.

2.1.2 Process description

In most cases, the AM process can be split into eight significant steps. It can vary depending on the technology used or the necessities of a specific design [10].

1 - Conceptualization and CAD: A 3-dimensional model represents the part made through CAD to reproduce the physical object digitally [10].

2 - Conversion to STL/AMF: STL is a simple way of describing a CAD model in terms of its geometry alone. The STL format triangulates the part introducing an approximation on splines, curves, etc. The errors introduced are acceptable as long as they are under the accuracy level of the machining process [11]. As mentioned above, the AM part will be composed of several layers. Therefore, this step forms the basis for the computation of these layers and the process resolution [10].

3 - Transfer to AM Machine and STL File Manipulation: After the STL creation, it can be transferred to the AM machine's environment, where it can still be repaired and smoothed [10].

4 - Machine Setup: Depending on the type of machine, a range of parameters will be available. These can be adapted for a better performance regarding the material chosen or the design. Examples of process parameters are layer thickness, laser speed, or hatch spacing. All of them weigh the final component quality [10].

5 - Build: In this step, we have the building phase. Since AM is mainly a process that builds a component from bottom to top, it is a layer-wise process. Visualizing and controlling the first layers are crucial for an exemplary manufacturing process to decide if the process will proceed correctly until the end. It is still prudent to routinely check if the building process is undergoing without errors [10].

6 - Removal and Cleanup: After the cooldown, the component is ready for extraction from the AM machine. Depending on the AM process, the needed steps can vary, but suffice it to say that all processes have some requirement at this stage. The cleanup stage may also be considered the initial part of the post-processing stage [10].

7 - Post-processing: Post-processing refers to the stages of finishing the parts for application purposes. At this point, components may be fragile or have construction supports that must be removed. Some applications may only require a minimum of post-processing. Other applications

may require careful parts handling to maintain good precision and finishing [10].

8 - Application: In this step, the built part is ready for use. It should be noted that one of the characteristics that are associated with AM processes is high surface roughness. Some AM processes inherently create parts with small voids trapped inside them, which could be the source of part failure under mechanical stress. In addition, some processes may cause the material to degrade during build or for materials not to bond, link, or crystallize in the desired way. In most cases, the properties are anisotropic. For most metal AM processes, rapid cooling results in different microstructures than those from conventional manufacturing [10].

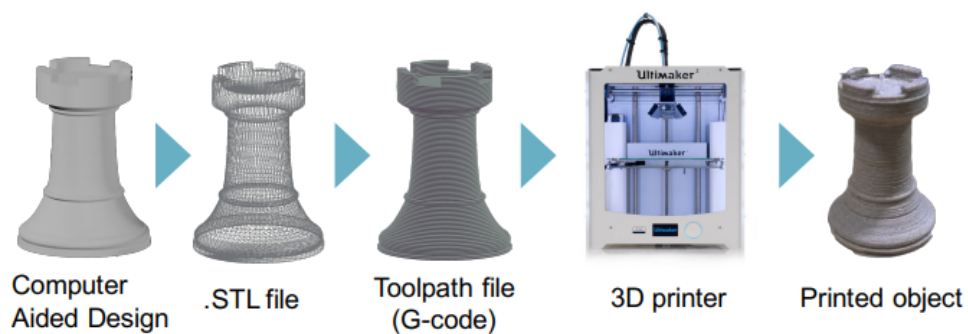


Figure 2.1: Exemplification of a 3D Printing process chain [12].

AM techniques are one of the most promising techniques for producing parts, neglecting the prototype development phase and the cost of the pre-series tooling and allowing the final user to have a prototype or a component that can be used shortly after the design phase [11]. Rapid prototyping matches the requirements of the new Unmanned Aerial System (UAS) research and industrial development for its ability to shorten product development time to have faster building parts to test [11].

2.1.3 Classification

The ISO/ASTM 52900:2021 standard classifies AM processes into seven different categories: [13]
BJT - Binder Jetting: process in which a liquid bonding agent is deposited to join powder-based material.

DED - Directed Energy Deposition: process in which focused thermal energy is used to fuse materials by melting as they are being deposited.

MEX - Material Extrusion: process in which material is drawn through a nozzle where is partially fused.

MJT - Material Jetting: process in which drop on demand approach of feedstock material are selectively deposited.

PBF - Powder Bed Fusion: process in which using thermal energy selectively fuses regions on a

powder bed.

SHL - **Sheet Lamination**: process in which sheets of material are bonded together to form a part.

VPP - **Vat Photopolymerization**: process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization

Although polymer printing techniques have progressed over the years, AM technology has been taken to a new level by the sophistication of metal AM techniques, which allowed for functional parts to be produced in various engineering and industrial applications [8].

2.1.4 Metal Additive Manufacturing

The initial usage of Additive manufacturing was non-metal primarily material, and only in the early 90s did it become possible to use the most used engineering material. After the first developments in binder jetting technology after it, the progression of capable laser technology paved the way to even more expansion [14]. After these pioneering breakthroughs, the research and development in this field are facing constant change.

As represented in Figure 2.2, there is direct and indirect MAM. The difference is related to the given objective for the building part, which on direct MAM is straightforwardly produced with the final specification desired. At the same time, indirect MAM is a sub-part of a conventional manufacturing process. Therefore, the latter cannot be uncoupled from conventional manufacturing processes [14].

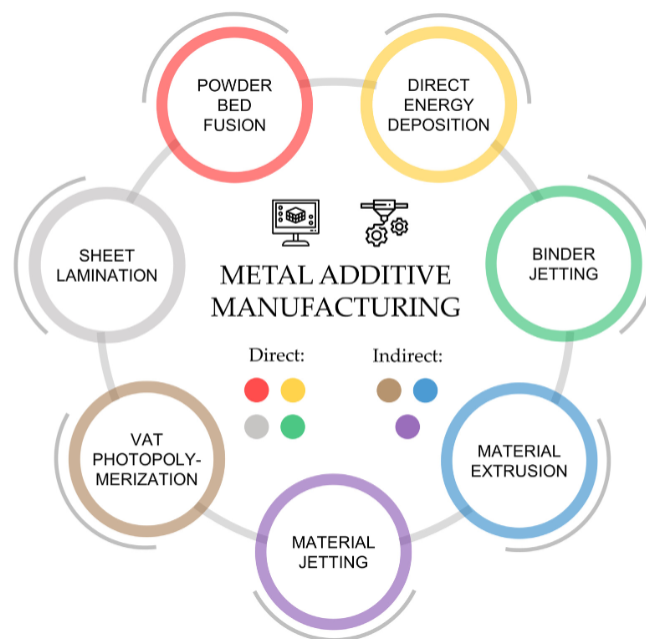


Figure 2.2: Additive manufacturing classification with their suitability to build metal parts [14].

Mainly the MAM process is centered on the categories mentioned previously: BJT, SHL, PBF, and DED, which are direct MAM. The remaining ones are indirect MAM, mainly used to build polymer and highly-filled polymer parts made from mixtures of metals or ceramic powders with polymers [14].

The type of AM process addressed in this work is the Powder Bed process, which has different ramifications, as seen in Figure 2.3. Hence, depending on the technology used, the required parameters for the printing process can change significantly [15]. The process chosen is a beam-based method called PBF.

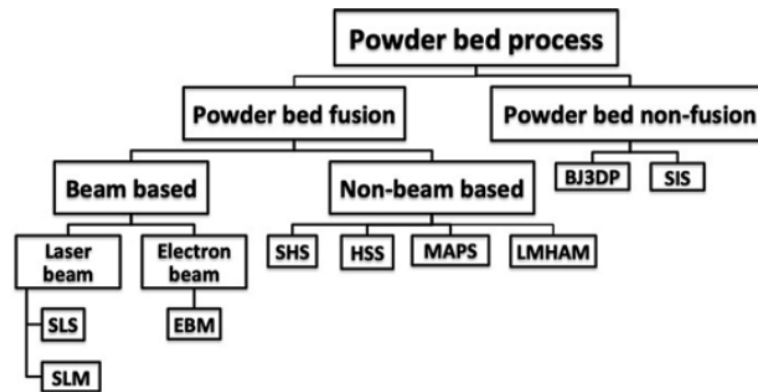


Figure 2.3: Powder bed classifications [16].

2.1.5 Powder Bed Fusion

PBF, as the name suggests, is an AM process where the building part emerges from powder. It is known to have a lower material deposition rate compared with other AM processes, such the most known rival AM process, DED. Moreover, the building layer thickness is intrinsically related to the powder thickness, depending on the material. In metal powder, SLM layer thickness can range from [20 – 100 μm] [17, 18].

The process starts with lowering the substrate model equal to the layer thickness. Afterward, the powder bed is recoated. The powder can be disposed by a vibration platform, hopper systems or even an opposite powder bed that goes up as much volume of the substrate goes down so after a blade or a roller can spread the powder in order to guarantee a smooth powder layer [15, 16].

There are several studies on the powder feed chambers since the higher the final build. More problems appear with the different densities and sizes of the powder caused by the compression under the powder weight on top. These problems can be fought by compressing the feeder powder bed or adapting the energy given to the upper layers [10].

After the recoating, it is time to scan the desired geometry by a heat source that usually goes by a laser or an electron beam. With the steps mentioned above, the PBF process is ready to repeat until the manufactured part is done.

The EBM and SLM share a common strategy of melting the powder to produce a final part. Notwithstanding, the SLS misleads with the "sintering" term, a mandatory post-processing technique vital for the SLS process. Since this process only confers the desired shape. A term more fitting for the SLS technique would be Selective Laser Partial Melting since it only joins the powder for a subsequent sintering process [16]. Therefore, SLM and EBM are the most promising techniques in PBF processes [19]. This work is sustained using SLM – LPBF technology.

2.1.6 Laser Powder Bed Fusion

On LPBF, the heat point source is a high-intensity laser light that, with the help of optical control equipment, allows the laser to follow a pre-defined two-dimensional scanning path to melt the wished part selectively [17].

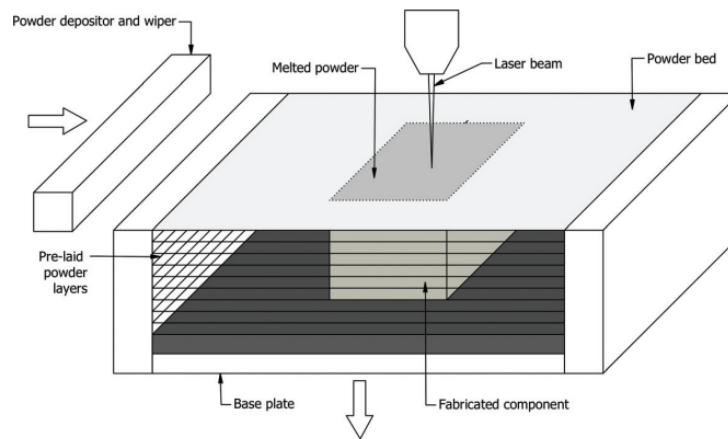


Figure 2.4: A schematic representation of SLM [20].

Most of the time, the laser is a fiber laser that presents magnitudes around 100 Watts, with wavelengths comprehended at the $[1.06 - 1.08 \mu\text{m}]$ range [18]. The laser characteristics cannot be expressed with only two parameters. There are numerous more, such as angle of incidence, beam diameter, beam divergence, etc. LPBF is one of the oldest MAM processes, which collected some years of research and experiments. To date, LPBF can achieve a deposition rate up to 0.1 [kg/h], and surface roughness in the range of $[10 - 20 \mu\text{m}]$ is achievable [14].

The melting process has a different complex phenomenon occurring at the same time. Fig. 2.5 helps to understand this interaction between the laser and the powder bed. Once the laser beam contacts the metal surface powder, some portion of the light is reflected, and the powder absorbs another [17]. The absorbed energy will raise the metal powder's temperature and form a localized melt pool. Since it achieved a liquid metal state, in most cases, this will create the necessity for a non-oxidative environment. Some examples of gases are nitrogen or argon, which will allow the desired effect of preventing metal oxidation during the fusion [18].

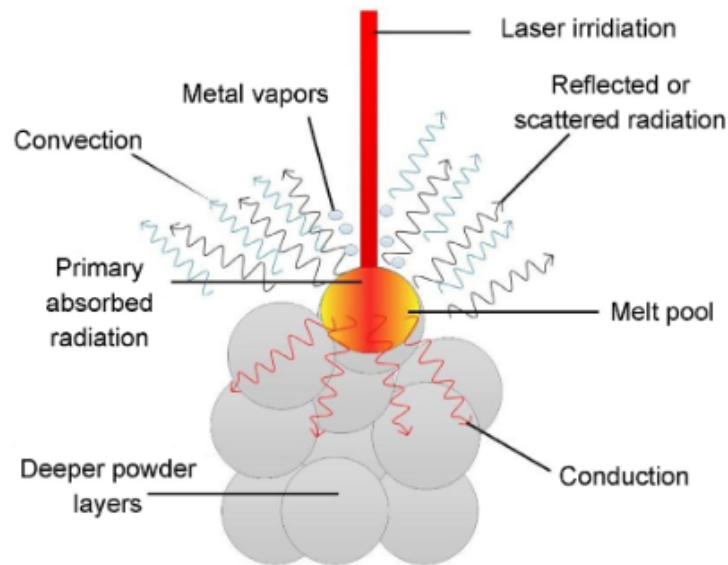


Figure 2.5: Schematic illustration of laser interaction with the metal powder particle during the selective laser melting process [17].

In LPBF, powder plays a crucial role, and it is common to think that any weldable metal should be a PBF, DED, and BJT processes materials [21]. However, at present, only a limited number of alloy systems are substantially developed [22]. Of these, we can highlight Titanium alloys, Inconels or Stainless Steels.

2.1.7 Process parameters

LPBF has over 50 process parameters, each impacting the part's final quality [18]. Figure 2.6 shows the four main categories of process parameters in SLM: laser-related, scan-related, powder-related, and temperature-related. Correctly choosing the parameters is essential to satisfy the wished part quality.

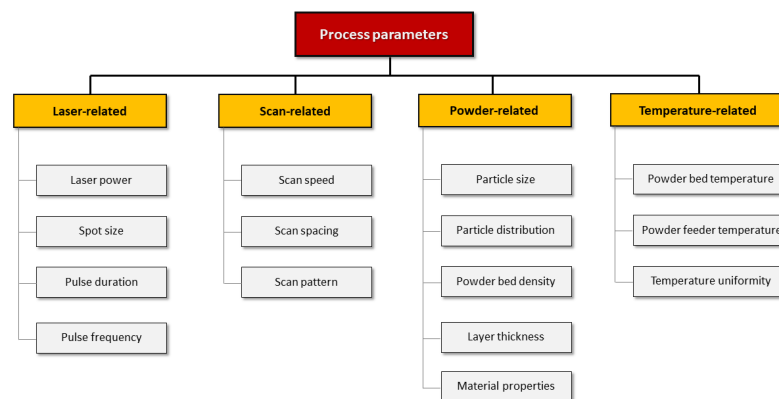


Figure 2.6: Controlling parameters in SLM process (Adapted from [23]).

Commonly, the process parameters are chosen at the beginning of the process. Even though it does not mean that they do not change during the process. A typical example is different velocity and power parameters when printing the part contours and the part bulk. In order to have a better surface finish, the contours must be carefully printed. Therefore, the energy density is lower to decrease the dross formation [18, 16, 24].

Following the latest developments, with the help of machine learning, it is already possible to create feedback loops to adapt some process parameters to generate manufactured parts with fewer defects. This concept will align with the new industrial revolution 4.0 and Smart Manufacturing such as Digital Twin [25, 26].

The hatch spacing, scanning speed, layer thickness, and scanning pattern stand out among the numerous parameters. The hatch spacing is measured by the distance from the beam center to the next beam center, as seen in Fig. 2.7. Furthermore, they are always smaller than the beam diameter. This is due to the Gaussian beam effect that presents a higher power on the beam center and decreases along the radius. The overlap will compensate for the reduced heat generation at the boundary of the beam [16].

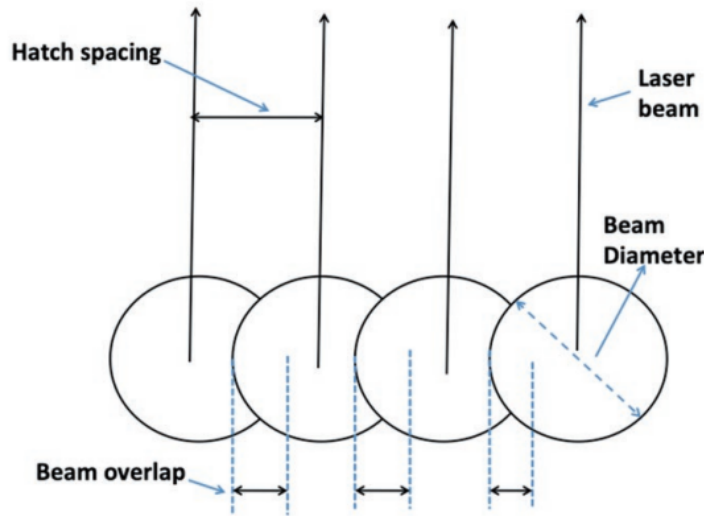


Figure 2.7: Schematic diagram of scan spacing [16].

The scanning speed is a critical controllable process parameter, impacting how long the laser power is applied to a particular spot. Usually, laser scan speeds are on the order of 10 to 100 millimeters per second [18, 16]. Scan speed and laser energy density are related as follows:

$$E_v = \frac{P}{S_d \times V_s} \quad (2.1)$$

where, E_v = laser energy density, P = laser power, V_s = scan speed, S_d = spot size. This is why the scan speed determines the melt pool length. A higher scan speed gives rise to more prolonged

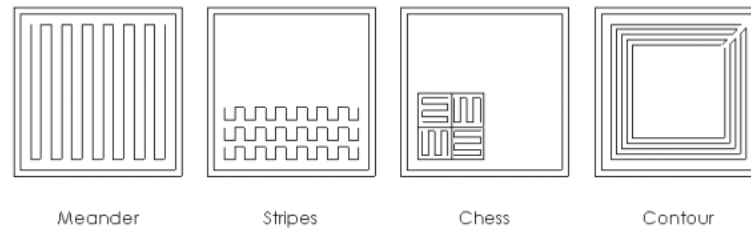


Figure 2.9: The four different scanning strategies: meander, stripes, chess, and contour [20].

and thinner melt pools, which have higher chances of breaking into several smaller melt pools due to Rayleigh instability [16].

The layer thickness also dramatically impacts the overall production speed since we can have more oversized layers on an excellent production volume. Alternatively, a small layer thickness increases the process precision [16].

Suppose the printed geometry presents a slope on the contours due to the slicing effect mentioned in Chapter 2.1.2 of a 3D CAD. The manufactured part will also have the effect displayed on the surface. This feature can be seen in Fig.2.8.

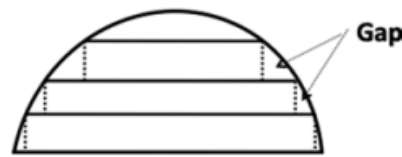


Figure 2.8: Schematic diagram of staircase effect [16].

The scan pattern is the pattern in that the beam scans the new layer. There are different ways to do it, and each behaves differently concerning the piece's geometry. The pattern directly impacts the heat surface distribution, affecting the microstructure. However, it is still hard to find a clear correlation between the scanning strategy and the mechanical properties generally because of the porosity level that each strategy causes [27, 28].

Common scanning patterns include hatches in arrays of parallel stripes, meander, chess, or contours from the outer edge of a part to the center, as seen in Fig.2.9.

One of the ongoing problems in AM is the optimization of the process parameters since they are usually experimentally optimized even though it is time-consuming and expensive.

2.1.8 Mechanical considerations

Currently, AM methods can manufacture high-strength components with more static strengths than their conventionally produced counterparts. Nevertheless, to understand how we can produce parts with interesting mechanical properties from AM, we must first understand the different phenomena in AM.

Residual stresses and deformations

The residual stresses generates distortion and contribute to crack formation [29]. There are two mechanisms responsible for generating residual stresses: The temperature gradient mechanism and the cooling down phase. The first one is caused by the high temperatures near the laser beam, where cracks tend to be formed to release the thermal stress, whereas in the cooling down phase model, the shrinkage of the material during the solidification or cooling can also generate internal stresses [30, 29]. In other words, when the laser beam leaves the melted spot, the instant after, it has a low yield stress. The melt pool continues its way, and the material yields in compression. After, the material will go through yielding. The newly solidified track will undergo a tensile stress state, while the previous tracks will experience a compressive state. These different internal stresses can lead to undesired distortions. So, prevention is of extreme importance [31]. There is currently some research to mitigate this effect, from scanning patterns, design compensation, and the most common, heat treatments [32, 30, 16].

Porosity

Porosity can have multiple origins, but all of them are usually detrimental to the mechanical properties of the component. Trapped gases, such as gas-atomized powder or moisture, can create porosity. It can also be generated by the collapse of a deep melt pool, often found at the start/end points of the scan tracks or when the linear energy density is too high. This porosity takes the name of Keyhole porosity [33, 34, 21, 26]. At the interlayers, it is possible to observe un-melted particles due to insufficient energy. This type of porosity has the name lack-of-fusion. An unstable melt pool will generate irregular pores due to hydrodynamic instability of the melt pool at a high energy density. This instability is attributed to the Marangoni force and recoil pressure. The wrong selection of process parameters also affects porosity. For example, choosing a large hatch spacing generates a lack of overlap, creating an intra-layer porosity [33, 34].

Cooling rate

The AM's particular rapid heating-cooling thermal cycle creates interesting microstructures such as microstructural banding. They are controlled by the material properties, the energy density, the part's geometry, and by any preheating of the substrate [22, 35]. Since most of the heat is extracted in the substrate direction, it results in preferred directionality in grain growth.

All in all, AM produces parts with a complex thermal history due to the repeated melting and solidification cycle. This behavior introduces different complexities not usually found in conventional manufacturing processes [35, 21].

2.1.9 Applications

The manufacturing world, often limited by design constraints, is witnessing a revolution as additive manufacturing progresses. AM created the possibility of “design for performance” rather than “design for manufacturing” [23].

Therefore, automotive, medical devices, and aerospace industries are the main areas for the usage of AM technology since it allows to cut the time and the costs of the pre-series tooling and allows to produce of a variety of components with functional testing purposes [11].

The ability to neglect the hardness of a material to manufacture with it allows the use of hard material, which otherwise would be impossible with the conventional manufacturing process. It has been an essential technique for medical use, such as dental prostheses (Fig.2.10) [3, 11].



Figure 2.10: Lasersintered CoCr Crowns [36].

Topology Optimization

Topology optimization is an innovative method to design advanced structures due to the design freedom that AM solutions allow. It can obtain high-performance and lightweight structures already used widely in aerospace, as seen in Fig.2.11 [3, 9].



Figure 2.11: Antenna bracket for RUAG’s sentinel satellite [3].

2.2 Modelling of Metal Additive Manufacturing

2.2.1 Introduction

The AM brought innovation and freedom to the design and manufacturing of components. However, there is still room for improvement. In order to make it a large-scale and widely used manufacturing process, it will need to achieve a level of standardization [35].

Nowadays, we already have some attempts to create closed-loop process controls that will promote AM's consistency and reproducibility [35, 25].

Another way is by simulating the AM process in order to better understand the different phenomena regarding the process. This will cut costs and sometimes shorten the time of choosing the best process parameters, enhancing the general quality of manufactured parts [5].

It is possible to run different types of simulations. The most commons are Thermal analysis, thermo-mechanical analysis, Multiphysics analysis, Microstructural analysis, and Topology optimization.

With respect of the numerical model for AM, we can classify into three different categories:

- **Micro-scale** - emphasizes the microstructural evolution, such as dendritic growth;
- **Meso-scale** - emphasizes the behavior of the melting pool, such as the keyhole regime;
- **Part-scale** - emphasizes the entire component behaviour, such as residual stresses.

The model developed during this work is a part-scale thermal model of LPBF.

2.2.2 Physics and scales in MAM

LPBF has a multi-physics nature. Different physical phenomena act simultaneously but also at different length scales. Material transformation takes place locally between 10 - 100 μm and lasts under 10 ms, but components from a few centimeters can take hours or days to build up [5, 31].

As seen in Chapter 2.1.5, a high-energy beam generates a melt pool. With this, numerous interaction happens at the same time. Interfacial forces gradually appear on the surface of the melt pool and act as the main drivers for the fluid flow in the liquid domain. The origin of these forces is the surface tension and the Marangoni effect, the latter also known as thermo-capillarity. The third force acting on the liquid domain is the recoil pressure. Under some special conditions, this force leads to the formation of keyhole depression that might lead to porosities. On top of the previous forces, these phenomena occur in a short time, which raises other problems from the analyses perspective [31].

Another significant phenomenon in MAM is the formation and evolution of residual stresses. The melting and cooling cycles generate internal thermal stresses, leading to deflection and worsening the final quality of the part.

Models and simulation tools are being developed at multiple scales to account for the complex structure of additive manufactured metals and to understand their performance response [5]. The

Figure 2.14 shows the importance of the heat transfer phenomena in both meso and part scales as the primary driver of MAM simulations [31].

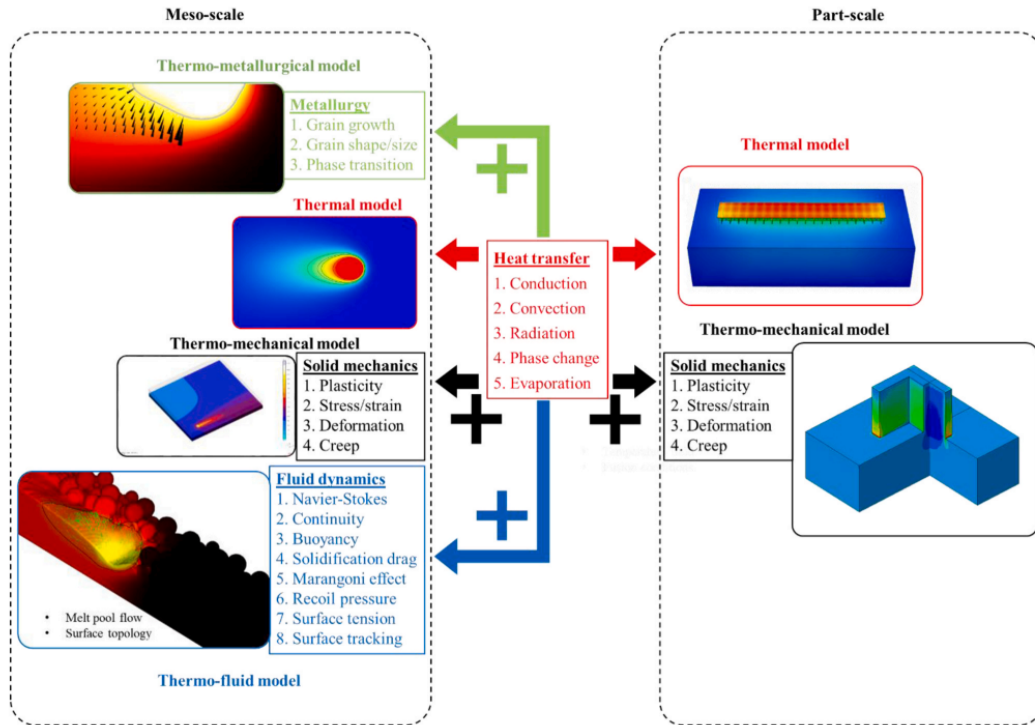


Figure 2.12: An overview of current possible modeling strategies for MAM at both meso- and part-scale [31].

When deciding which type of information will be needed, the model's length scale will need to be decided. If the objective is to study porosity, a mesoscale length will be needed with a CFD model. If the macroscopic deformations are the wished output, a mechanical FEM model at part scale is the proper option. It is also possible to generate models that feed other models, such as a coupled thermo-model by coupling heat transfer to a mechanical solver [31].

2.2.3 Micro and Meso scale models

At meso and micro length, we are at the scale of 10^{-6} to 10^{-3} m where all the previous mentioned forces are involved. There are different approaches to model heat transference, but the most powerful model is the multi-physics CFD model, where even the powder particles are explicitly represented. It is specially used to study the lack-of-fusion and keyhole porosities [5, 31].

When focusing on the micro-scale, it is paid attention to the microstructure closely related to the solidification mechanism. The grain boundaries are adequately studied where, for example, fundamental interfacial properties such as surface tension anisotropies should be possibly studied by atomistic simulations. At this scale, the main focus is the solid-liquid interface. In Figure 2.13, an example of growth grain simulation along a melted track can be seen [26, 5].

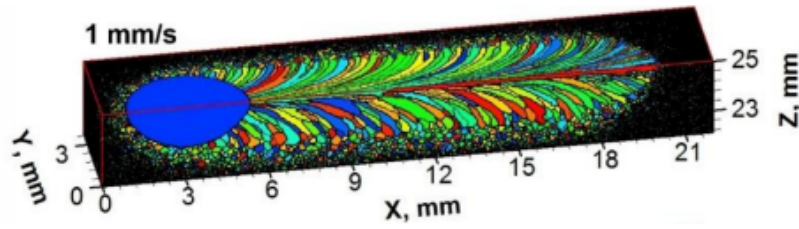


Figure 2.13: KMC simulation of grain structures in a weld [37].

On the mesoscale, the focus is on the liquid state found at the melt pool in the case of MAM. The thermo-fluid behavior is studied to understand and predict defect such as keyhole porosity. Nevertheless, even for such a well-behaved model, some problems, such as denudation, are neglected to make the simulation feasible [26, 31]. Figure 2.14 is shown an example of thermo-fluid during LPBF.

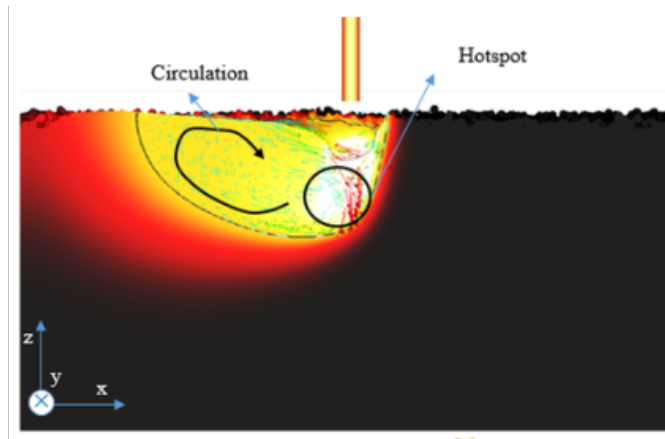


Figure 2.14: Close up into a mesoscale LPBF simulation [7].

However, these high-fidelity models come with a cost. It requires a vast amount of CPU and is limited to a few tracks or layers. Therefore, applying a mesoscale simulation to a full-scale component is still not feasible with the existing resources [31].

However, it is still possible to develop models where conduction is the primary heat transfer mechanism, while the others are neglected. With this, it can save some time, but in the end, it should only be used in a sensitive case to compare rather than extract absolute values [31].

2.2.4 Part-Scale models

As mentioned, applying the same methodology to an entire component would require a sufficiently fine mesh size and a small time step to obey the convergence criteria in order to simulate it. Therefore, it was necessary to develop new methods that could capture the behavior of the whole component and, at the same time, be able to simulate it. In order to do that, in most cases, the phenomena occurring at the laser-powder particle interactions are neglected. FEM methods mostly carry these simulations [5, 38].

Some of the main thermal part-scale methods are briefly presented below:

Flash Heating

This method is based on lumping the layers in a "meta-layers" block. They are activated at the moment when the first particle should be activated. At this point, a body heat flux quickly heats the meta-layer in a brief period. This originates the name of "Flash heating". However, this method requires calibration to achieve the correct heating time and correctly reproduce the overall heating mechanism [6]. This method is the main goal for the modeling of the current project. Therefore, a further explanation can be found in Chapter 3.2.

Sequential Flash Heating

Sequential flash heating came to solve one of the issues of the previous method. Since FH is a layer-by-layer method, it loses the effect of the scanning pattern. With SFH, it is possible to create lumped hatches that can take into account the effect made by the scanning strategy. However, this comes with expressive computational effort compared with the FH [6]. In Fig.2.15, the different meta-layers of this method can be seen.

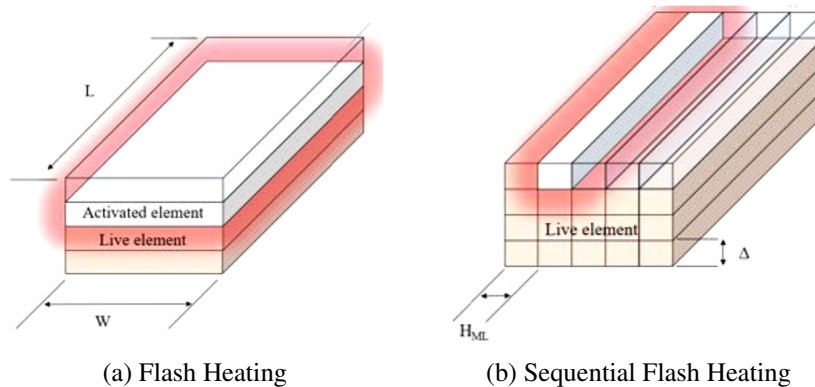


Figure 2.15: Activation strategy in the FH and SFH methods [6].

Gradual Heating

This method has many similarities with FH. However, it will be smoother heating instead of heating up in a short period. Since the component has more time to transfer the heat, it will contribute to lower peak temperatures. This can prevent the meta-layer from reaching melting temperatures, preventing the thermomechanical simulation from becoming reliable [6].

Multi-Shot Super-Layer

The Multi-Shot Super-Layer deposition method has an essential difference from the FH method. In the FH, if we lump five layers, we will only have one heating moment that will try to reproduce the heating effect of 5 layers. However, with the multi-shot, that meta-layer will be heated up five times, evenly distributed during the step time, allowing for heat and cooldown, reproducing more fairly the thermal cycles and stresses of the manufacturing processes [39].

It is worth mentioning well-known thermomechanical simulation methods such as the Inherent strain method or even Agglomerated Heat Source. These methods have been in practice longer and therefore present more optimizations today compared with the previously mentioned.

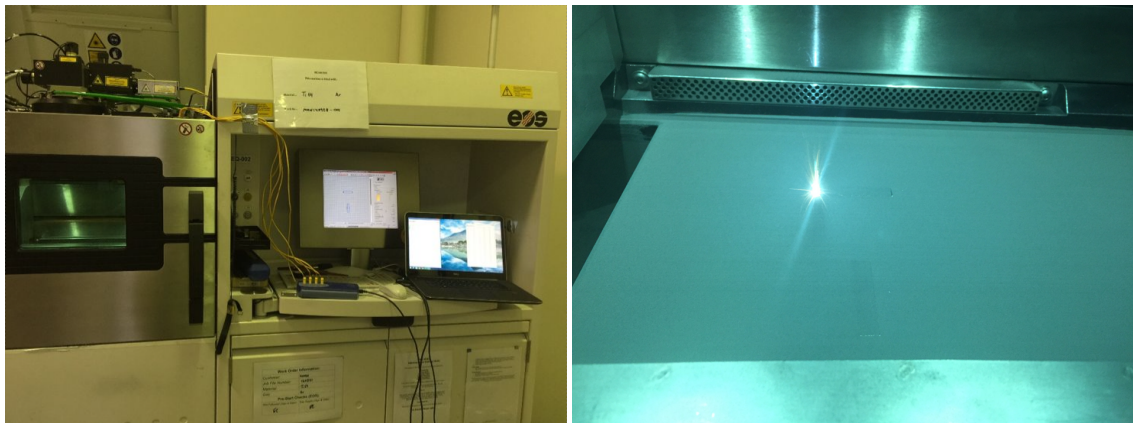
Chapter 3

Methodology

This chapter intends to present practical information on the Metal Additive Manufacturing experiment and the simulations after. The chapter includes the experimental setup and the process monitoring properties used. A second section related to the modeling techniques used to create the numerical models in ABAQUS, and a third section focused on the FEM Simulations performed.

3.1 Experimental Setup

It was decided to use an already made experiment to start working on a validation model. The main focus of the experiment performed at Monash Center for Additive Manufacturing was the part quality when some manufacturing variables are changed, such as recoating, gas flow, and laser beam irradiation [40, 41]. The SLM experiment was conducted on an EOSINT M280 from Electro Optical Systems (EOS) GmbH. The experimental setup can be seen in Fig.3.1a.



(a) EOS 280 M with the data extraction devices

(b) Image during the manufacturing process

Figure 3.1: Pictures taking during the experiment shared by Dr. Zhuoer Chen.

The material chosen for the experiment was a gas atomized Ti-6Al-4V powder since it has received much attention due to its high strength-to-weight ratio [2]. The powder used had a feedstock distribution of D10, D50, and D90 of 16 μm , 30 μm , and 50 μm [40, 41].

Table 3.1: Chemical composition of Ti-6Al-4V powder [41].

Element	Al	V	C	N	H	Fe	Ti
%	5.84	4.00	0.013	0.004	0.003	0.098	bal.

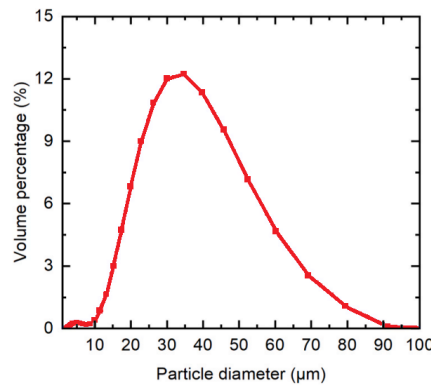


Figure 3.2: Particle size distribution of Ti-6Al-4V feedstock powder (Adapted from [41]).

At the beginning, a temperature of 100 $^{\circ}\text{C}$ was imposed on the substrate, and the EOS M280 chamber was pre-filled with Argon gas until the oxygen context was lower than 1000 ppm [40].

A carbon fiber blade was used for recoating the powder. The laser beam has a $D4\sigma$ of 80 μm under a laser power of 200 W. The EOS build preparation software applied a nominal laser beam diameter of 100 μm . The F-theta lens has a working distance (from the front optic to the workpiece) of approximately 500 mm [41].

The specimens were built with the process parameters shown in table 3.2. The laser was set to scan in a unidirectional pattern along the Y axis as it can be seen in Fig.3.3, with the default contour scan setting deliberately deactivated.

Table 3.2: Process parameters adopted by the EOS Machine [42].

Power input	280	[W]
Scanning speed	1200	[mm/s]
Layer thickness	30	[μm]
Hatch distance	140	[μm]
Beam offset	15	[μm]
Recoat time	9.36	[s]
Relocation time	0.03	[s]

3.1.1 Geometry and *in-situ* Process monitoring

In the experiment, two geometries were used that shared the same volume and a 45 angle to the horizontal plane. They also had a cross-sectional dimension of 10 mm $\times$ 15 mm. However, their orientation was perpendicular to each other, as shown in Fig.3.3.a.

In the same figure, we can see a particular step of this experiment: building up until a height of 15 mm from the baseplate and interrupting it. Afterward, the powder is removed and the thermocouples that touch the inclined surfaces are inserted near the 15 mm level, just far enough to not be melted, as shown in Fig.3.3.b.

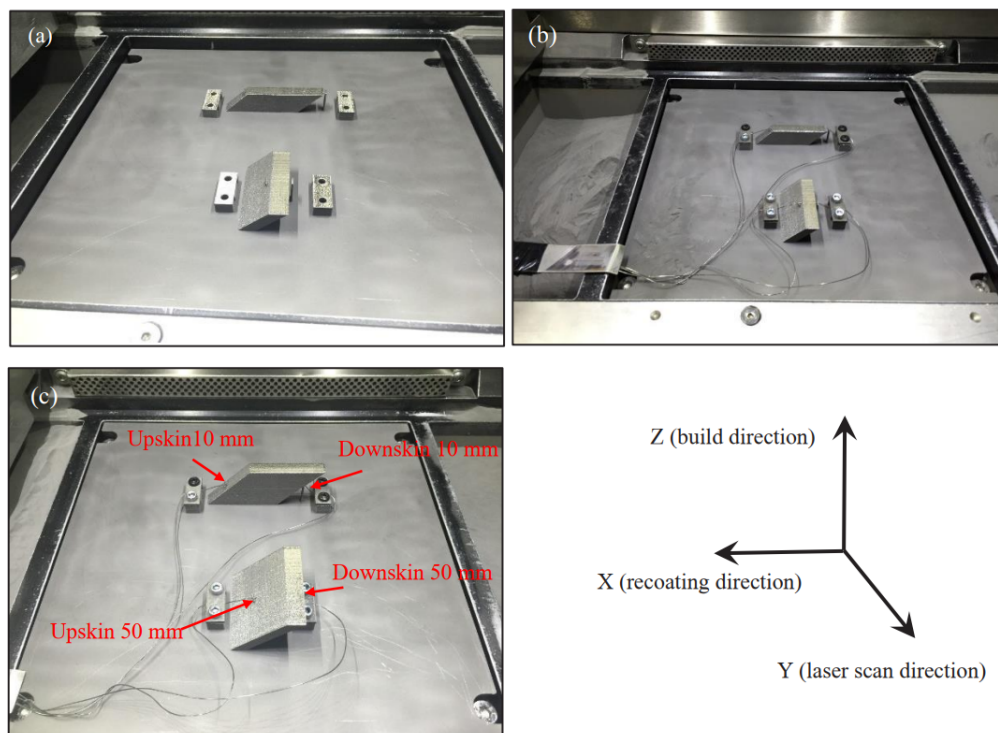


Figure 3.3: Experimental set-up for the measurement of temperature at part surface during the SLM process [40].

In Fig.3.4 it is possible to better understand the work flow during the experiment.

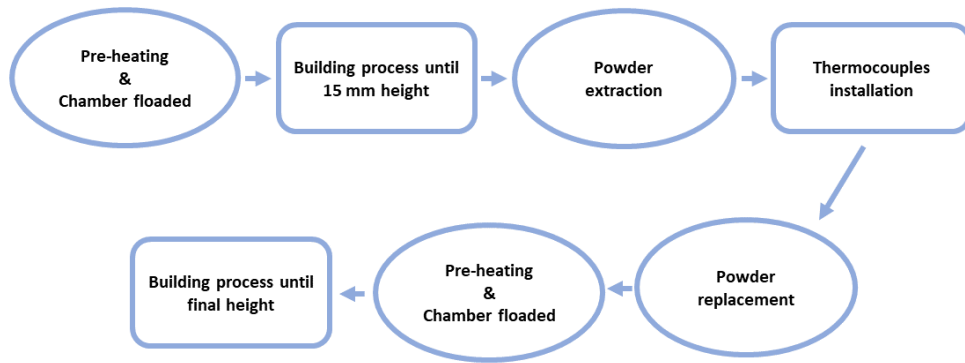


Figure 3.4: Schematic diagram of the experiment.

Next, the chamber is filled in with powder, where the thermocouples and the specimens are all buried in the powder bed. The chamber is flooded with argon, and the build plate is heated up to 100°C to restart the process up to 40 mm total height. The data channels are named after their surface orientations (upskin or downskin) and scan vector length (10 mm or 50 mm) and are pointed out by arrows in Fig. 3.3.c.

The thermocouples were a K-type with 0.5 mm in diameter and a response time $t_{90\%}$ (time to reach 90% real temperature) of 0.06 s. A data-logger recorded the data at a frequency of 1 Hz [40]. Figure 3.5 helps to identify the thermocouple position on the 50 mm specimen. They are the essential points of this analysis since they are where all the information is extracted.

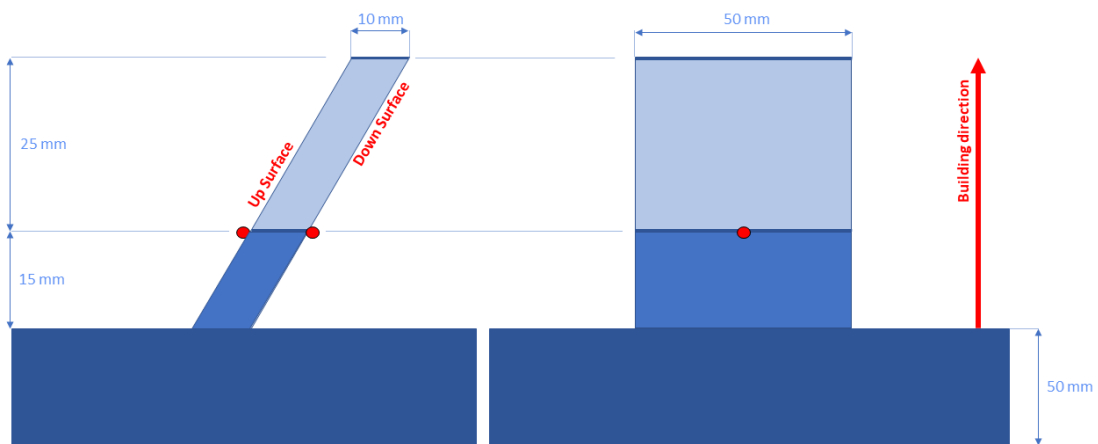
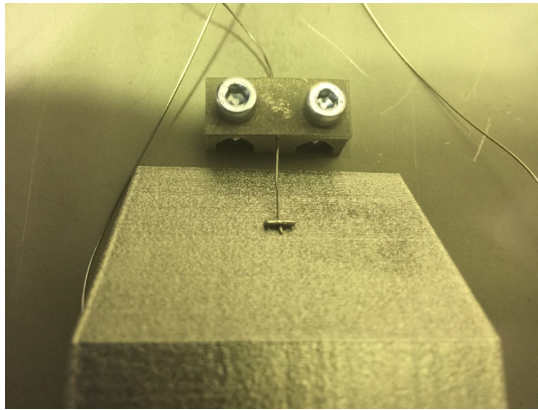
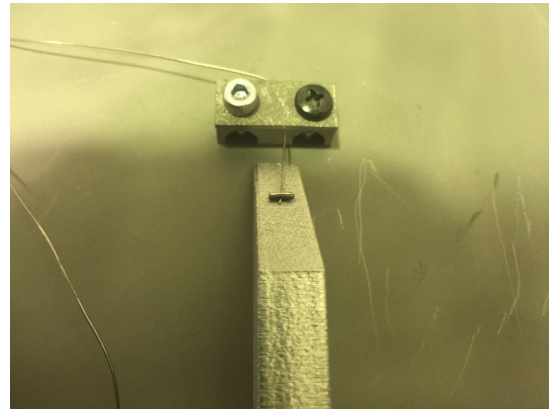


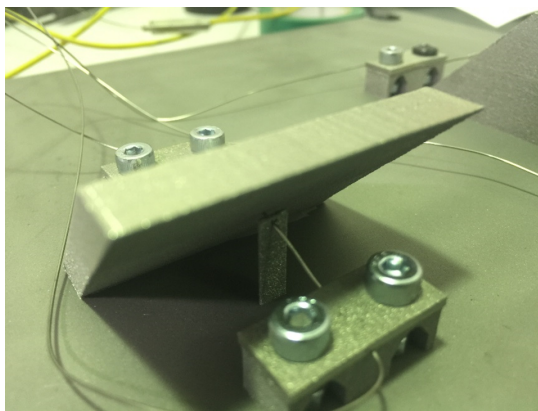
Figure 3.5: Representation of the 50 mm specimen and the relative thermocouple position and the identification of the up and down surface.



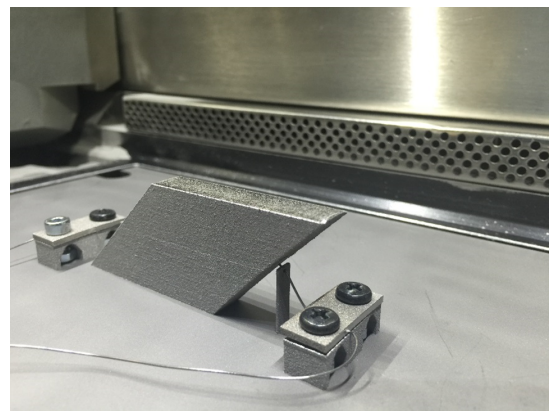
(a) Up Surface 50



(b) Up Surface 10



(c) Down Surface 50



(d) Down Surface 10

Figure 3.6: A closer look into the Up's and Down's surfaces (Shared by Dr.Zhuoer Chen).

In Fig.3.6, it is possible to see with a closer look at the thermocouple touching the Up and Down surfaces after the specimens are manufactured, and the powder removed.

3.2 Numerical Modelling

The main objective of the present work, as stated in the introductory chapters, is to develop a well-behaving thermal model that can represent an LPBF process without entering the mesoscale with its inherently excessive computational time due to the phenomena's complexity. All of this while maintaining physical reliability [1, 7, 4]. With such a model created, it would be possible to try new process parameters by simulating them without incurring a trial-and-error process with actual AM machines, saving time and money. During the model's development, experimental results were used to help calibrate the numerical model [40]. At a later stage of the project, a mathematical code is developed to cross information from *in-situ* monitoring data with the simulation data, marking the first steps for a possible digital twin of the AM physical process:

1. Develop and validate a thermal model for a geometry without overhang [42] (can be seen with further detail at Appendix A).
2. Develop and validate a thermal model for a geometry with overhang [40].

Initially the test of the thermal model for more complex geometries, such as channels, was intended, to ensure the model's reliability. However, the achievement of the first validation came at a later stage of the project.

The following model is focused on the experiment described in Section 3.1.

All simulations were executed in the High-Performance Computing (HPC) cluster of DTU, with eight cores used for each run. The simulations were built in the FEM-based commercial software package ABAQUS / CAE 2018 using the FH method generated by Python scripts.

3.2.1 Flash Heating

As shortly described in Section 2.2.4, FH is a method based on lumping layers that reduces computational time and resources in part-scale simulations with the inherent cost of losing local thermal accuracy. For a conventional gradual heating layer-by-layer model, the loading time of the volumetric heat source is equivalent to that of the actual experimental layer build time. In contrast, for FH, it is a fraction of the actual. This will allow reaching temperatures above the $T_{melting}$ to originate residual stresses. However, since this model ignores the real melt pool, laser heat sources, and scanning approach, its application is limited.

FH is applied to LPBF by activating the geometry in multiple ways, depending on the desired level of fidelity. The greater the number of hatches, the higher the fidelity, and the longer the computation time. When a layer/hatch is activated, thermal energy is supplied for a brief period, referred to as the contact time Δt_{cont} , during which the heat is carried within the material. In this model, we only focused on a layer partition rather than a hatch-by-hatch methodology.

When constructing an FH model, it is essential to comply with both time and energy consistency. The concept of time consistency relates to the activation times of the layers. At the start of the simulation, all patches are disabled unless the first layer with its respective heating effect.

Then, successive layers should be deposited with a progressive activation corresponding to the experimental deposition timings. To have a numerical model that respects the physics underlying melting time, the quantity of heat delivered to the layer in simulations must match the amount of energy supplied to the powder during the scanning. These two requirements are essential for ensuring the validity and reliability of the simulation since they must demonstrate the correspondence between the numerical model and the experiment.

Lastly, to ensure the accuracy of the FH approach, Δt_{cont} must be much shorter than the layer deposition time of the considered meta-layer, Δt . The deposition should be heated for a brief time to ensure that the melt phase is achieved and to allow heat energy to conduct throughout the remainder of the geometry. If $\Delta t_{cont} \rightarrow \Delta t$, the maximum temperature of the deposited material will decline until there is no pool of liquid melt. As previously stated, this procedure is known as Gradual Heating (GH).

Governing equations

In the analysis for the current project, the melt pool and related phenomena are not considered. Therefore conduction is the predominant mechanism of heat transfer inside the component.

The equation for transient heat conduction that governs thermal analysis is:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) - \rho \cdot \Delta H_{sl} \cdot \frac{\partial f_{liq}}{\partial t} + \dot{Q}_v''' \quad (3.1)$$

where ρ is density (kg m^{-3}), c_p is specific heat capacity ($\text{J kg}^{-1} \text{K}^{-1}$), T is temperature (K), t is time (seconds), and k is thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$). H_{sl} is the latent heat of fusion (J kg^{-1}) and Q is the volumetric heat source (W m^{-3}).

The sum of the liquid and solid fractions, denoted by f_{liq} and f_{sol} , is one. During the solid-to-liquid phase transition, the liquid fraction is considered a linear temperature function.

$$f_{liq} = \begin{cases} 1 & T \geq T_{liq} \\ \frac{T - T_{sol}}{T_{liq} - T_{sol}} & T_{sol} < T < T_{liq} \\ 0 & T \leq T_{sol} \end{cases} \quad (3.2)$$

For considering the phase transformations during the solidification process, the material properties will be averaged over the solidification interval using the liquid fraction and solid fraction.

$$k = f_{sol} k_{sol} + f_{liq} k_{liq} \quad (3.3)$$

$$c_p = \frac{\rho_{sol} \cdot C_{p,sol} \cdot f_{sol} + \rho_{liq} \cdot c_{p,liq} \cdot f_{liq}}{\rho_{sol} \cdot f_{sol} + \rho_{liq} \cdot f_{liq}} \quad (3.4)$$

$$\rho = f_{sol} \cdot \rho_{sol} + f_{liq} \cdot \rho_{liq} \quad (3.5)$$

Ignoring the material laser interaction with the powder and using an equal volumetric heat source for a predetermined contact time. The input energy of the layer can be computed using,

$$U_i = \eta \cdot P \cdot t_f \quad (3.6)$$

Where U_i is the input energy (J), η is the power absorptivity (-), P is the laser power input (W), and t_f is the time required to scan one layer (s).

But t_f is given by,

$$t_f = \frac{A_\Omega}{H \cdot v_{laser}} \quad (3.7)$$

Where A_Ω is the top surface area of the layer (m^2), v_{laser} is the laser scan speed ($m s^{-1}$) and H is the hatch distance (m). The top surface area is also given by,

$$A_\Omega = W * L \quad (3.8)$$

Where, W is the width of the part (m) and L is the length of the part (m), by substituting equation 3.8 in equation 3.7,

$$t_f = \frac{W * L}{H \cdot v_{laser}} \quad (3.9)$$

Substituting equation 3.9 in equation 3.6,

$$U_{i,\delta} = \eta \cdot P \cdot \frac{W * L}{H \cdot v_{laser}} \quad (3.10)$$

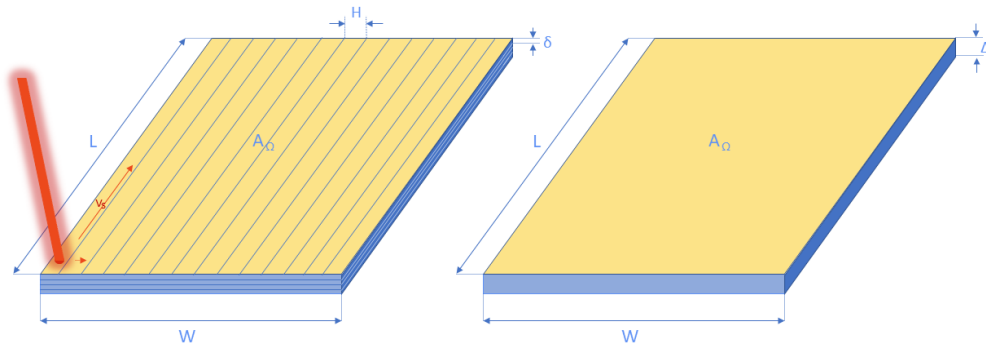


Figure 3.7: (Left) Actual layer (with thickness δ) and (right) meta-layer (with thickness Δ).

Figure 3.7 shows that for flash heating, the component with actual layer height δ (m) is combined with numerous layers to calculate meta layer height Δ (m). Consequently, the ratios of their layer input energies can be represented as follows:

$$U_{i,\Delta} = U_{i,\delta} \cdot \left(\frac{\Delta}{\delta} \right) \quad (3.11)$$

Where U_{Δ} is the input energy of the layer for the metalayer. To determine the volumetric heat source for the metalayer, divide equation 3.11 by the layer's volume and contact time, Δt_{cont} (s),

$$\dot{Q}_{\forall}''' = \frac{U_{i,\Delta}}{\Delta t_{cont} \cdot (H * L * \Delta)} \quad (3.12)$$

Further substituting equation 3.11 and equation 3.10 in equation 3.12,

$$\dot{Q}_{\forall}''' = \frac{\left(\eta \cdot P \cdot \left[\frac{W * L}{H \cdot v_{laser}} \right] \right) \cdot \left(\frac{\Delta}{\delta} \right)}{\Delta t_{cont} \cdot ([W * L] \cdot \Delta)} = \frac{\eta \cdot P}{H \cdot v_{laser} \cdot \Delta t_{cont} \cdot \delta} \quad (3.13)$$

This will be the primary equation to model the volumetric heat source for FH's meta layers.

Element birth and death

The material deposition in additive manufacturing is usually modeled by activating the elements as the powder material gets in contact with the heat source. The most well-known approaches are: (1) the use of quiet or (2) inactive elements. In the quiet approach, the elements are present in the analysis but are assigned properties, so they do not affect the analysis, for example, zero thermal conductivity. In the inactive element approach, elements are not included in the analysis until the related material has been added and further explanation is presented immediately. There is also a hybrid quiet inactive metal deposition method that combines both methods into one, proving useful in some cases [43, 42].

In this work, the inactive element method is chosen for the element birth and death methodology.

In this method, the elements representing metal deposition zones are omitted from the analysis, and only the nodal degrees of freedom related to active elements are taken into account. Implementation numerically requires computing the element residual and Jacobian for only the active elements and solving for only the active nodal degrees of freedom. Some advantages of the inactive element method are that Element residual and Jacobian computations are conducted only for active elements as well as that only the active nodal degrees of freedom are addressed at any given time, resulting in the linearization of smaller algebraic systems via Newton–Raphson [43]. However, one of the most significant downsides of the inactive element method is that every time elements are activated, the equation numbering and solver startup must be redone. Therefore this may counteract the computational benefit of reducing the number of active degrees of freedom [43, 42].

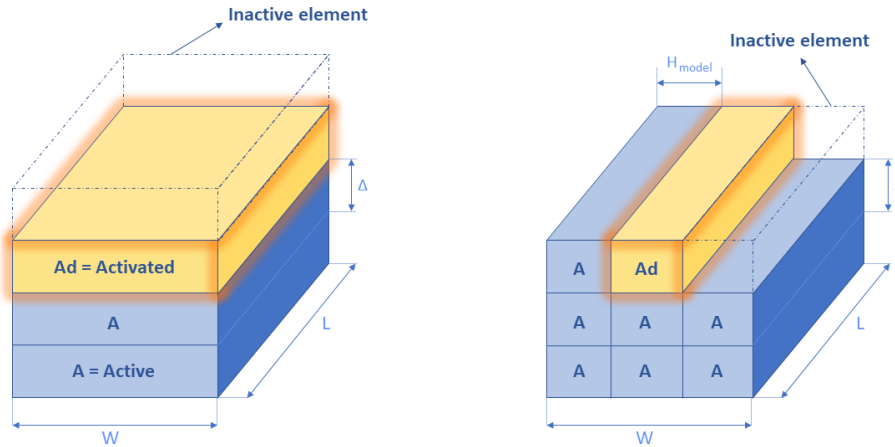


Figure 3.8: A schematic overview of the element birth and death methodology. On the left FH and the right SFH.

The inactive element method categorizes the elements of the finite-element mesh as either active, activated, or inactive [42]. Active elements are those elements that represent the building platform and those that the metal deposition process has activated; Activated elements are those influenced by the energy input at the current time step but were inactive before this instant; Inactive elements have not yet been incorporated into the computational domain.

In Figure 3.8, we can see a schematic representation of the inactive element method.

The activation sequence carefully complies with the original experiment's timings, and there is a period of inactivity between successive layers to replicate the powder spreading process. This strategy also results in significant computational savings because the model does not have to solve the thermal field as the laser heat source scans the layer, allowing for more extended steps in the computational procedure.

Time consistency

Total sweep time (t_f) is the time required to heat/load a whole layer. However, the procedure involves two stages: heating and cooling, where (t_{cool}) is the cooling time for each layer. The cooling time is the total time the laser is not in contact with the powder and the time necessary to spread a new layer of powder for printing. ($t_f + t_{cool}$) will be the required time to complete the procedure for each activated layer. The heating/loading time for FH is constant regardless of these times (Δt_{cont}).

Boundary conditions

In PBF processes, the manufactured part is permanently in touch with the powder bed. Moreover, this has a significant effect on dissipating some heat and also building a thermal battery in the surrounding of the piece. Therefore, it was decided to consider it since it ignored the Powder Bed

domain. Ignoring the powder bed from the simulation will impact the accuracy of local thermal history. Therefore, the heat transfer from the part to the excluded region is then accounted for with an equivalent heat loss boundary condition at the solid-powder interface. The value of extracted heat from the component to the powder is subject to validation with the experimental data [42].

The convection and radiation of heat to the environment from the top surface are given by,

$$-k \frac{\partial T}{\partial z} = h_{amb} [T - T_{amb}] + \varepsilon \sigma [T^4 - T_{amb}^4] \quad (3.14)$$

Where, h_{amb} is ambient convective heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$), ε is the surface emissivity (-) and σ is Stefan Boltzmann constant ($\text{W m}^{-2} \text{K}^{-4}$).

It is critical to accurately model thermal conduction, convection, and thermal radiation to ensure that temperature gradients are correctly measured. During the AM process, previously exposed material surfaces are replaced with new material, and new free surfaces are produced over time. Abaqus keeps track of the changing free surfaces representing the current shape of a printing component at any given point in the build and only applies film and radiation loadings to those surfaces. In both convection and radiation mechanisms, the top surface is applied a $T_{amb} = 35^\circ \text{C}$, a little bit higher than the standard 25°C to account for the heating effect inside the printing chamber [42].

The surface emissivity exposed to the atmosphere is a critical characteristic of the radiation, and the selected value was 0,4.

In Figure 3.9, it is possible to see the different heat transfers initially planned for the thermal modeling.

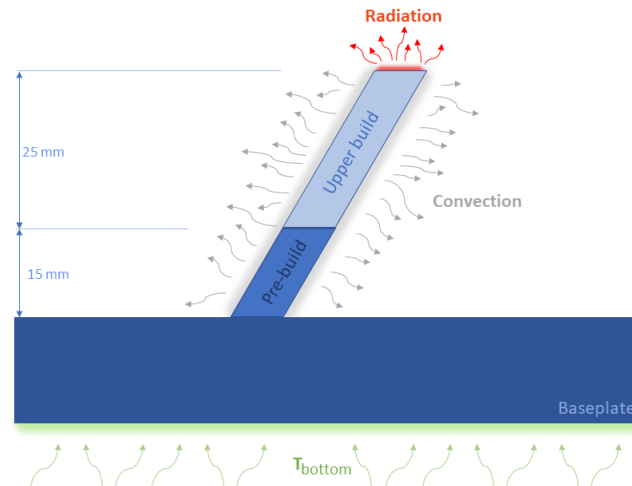


Figure 3.9: Schematic representation of thermal boundaries. The temperature at the bottom of the baseplate (green). Powder Convection around the manufactured part (gray). Radiation on top of each last layer (red).

Besides the top surface heat transfer, there is also the imposed temperature at the bottom, which minimizes the residual stresses and the HTC around the component to emulate the powder bed domain. The bottom temperature, as described in Section 3.1, has the value of $T_{bottom} = 100$ °C, and the sink temperature of the powder bed is 100 °C in order to share the exact temperature of the bottom sink.

3.2.2 Thermal model of LPBF

The numerical model follows the FH method mentioned before and is constructed in ABAQUS using Python code. Its overall form is depicted in Figure 3.10. First, the code is provided with all necessary simulation parameters, the most critical of which are the contact time Δt_{cont} , the scanning speed v_{laser} , and the realistic (δ) and model (Δ) real thicknesses. f_{lump} will be the ratio between $\frac{\Delta}{\delta}$. The geometry is then imported into the Part ABAQUS environment. The geometry is given through a .sat file, the extension that ABAQUS can read most easily. The geometry includes all pertinent geometrical data, including the component's length and height and the baseplate's height.

Afterwards, ABAQUS executes numerous instructions through the code. The manufactured part is separated from the baseplate (designated as a distinct entity). Based on the supplied value of f_{lump} , an $\left\lceil \frac{Build_{height}}{\Delta} \right\rceil - 1$ number of Datum planes are then defined between the already built component (15 mm height from the baseplate) and the building's top surface. These are utilized to separate the building specimen into distinct layers. When the last layer cannot comply with the rule of being the same thickness as Δ , it will agglutinate the last layer to the preceding layer, producing a layer with a thickness between $\Delta < thickness_{last\ layer} < 2 * \Delta$. This will enable the selection of any f_{lump} without compromising the model's geometrical limitations.

It is customary to identify the various partitioned components and surfaces for the eventual assignment of loads, boundary conditions (BC's), and other information. Therefore, each component is given names using the Sets and Surfaces settings. These are then specified for each layer, surface, baseplate, and pre-build geometry (first 15 mm).

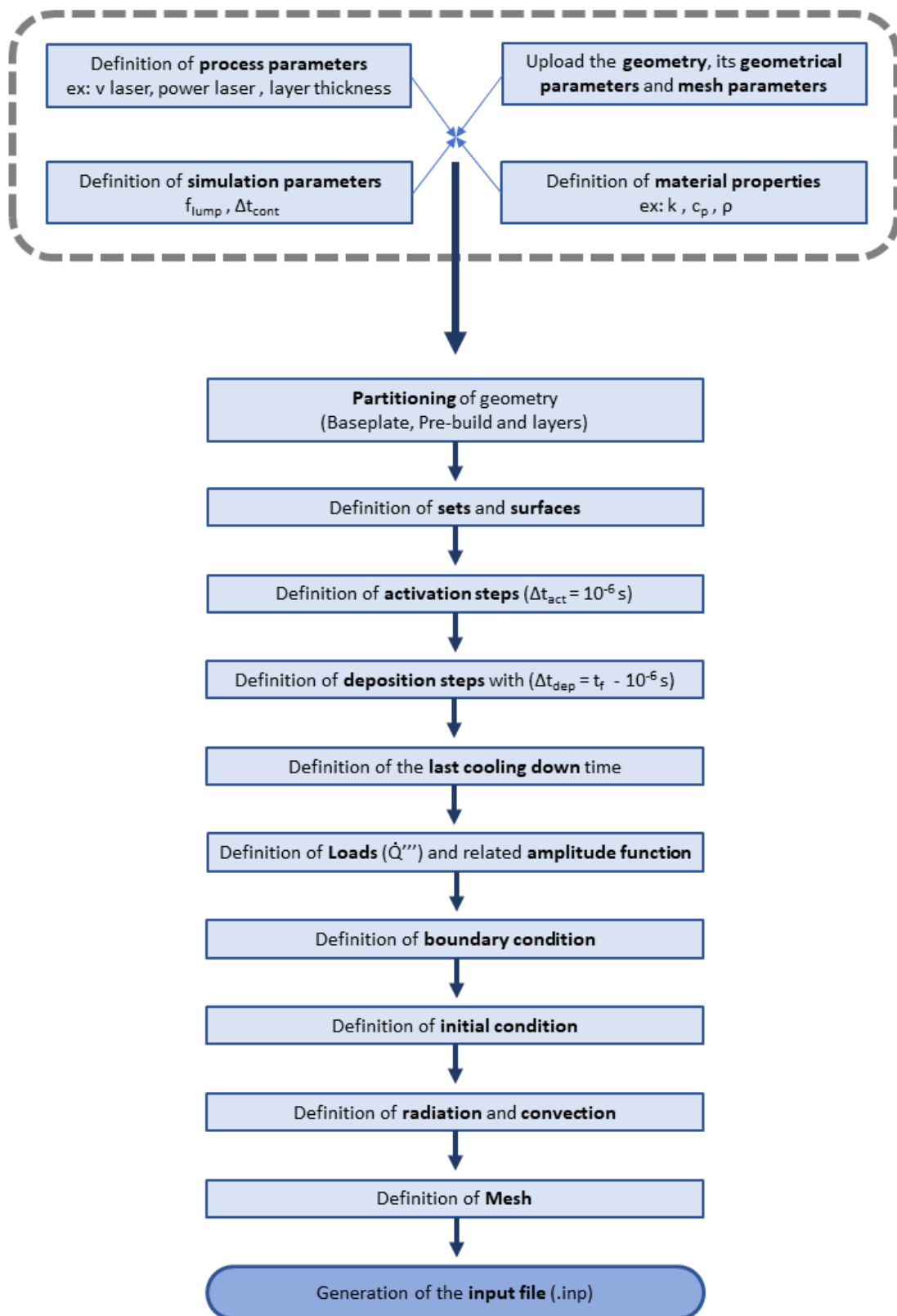


Figure 3.10: Structure of the Python code for ABAQUS implementation.

Then, material properties are provided to the program. As MAM modeling needs heating beyond the liquidus temperature, temperature-dependent material characteristics are employed up to these values. ABAQUS linearly interpolates the values inside the provided temperature-dependent data points to extract values at each specified temperature. To numerically calculate Equation 3.1, it will be needed thermal conductivity k , density ρ , and specific heat at constant pressure c_p . These temperature-dependent characteristics of Ti-6Al-4V Titanium alloy are shown in Figures 3.11, 3.13 and 3.12. It also incorporates the latent heat ΔH_f , which is the extra quantity of heat emitted during solidus and liquidus temperatures. According to the same source, this is equal to $\Delta H_f = 286 \text{ kJ/kg}$. Also included are the solidus and liquidus temperatures: T_{sol} equals 1620.0°C and T_{liq} equals 1654.0°C .

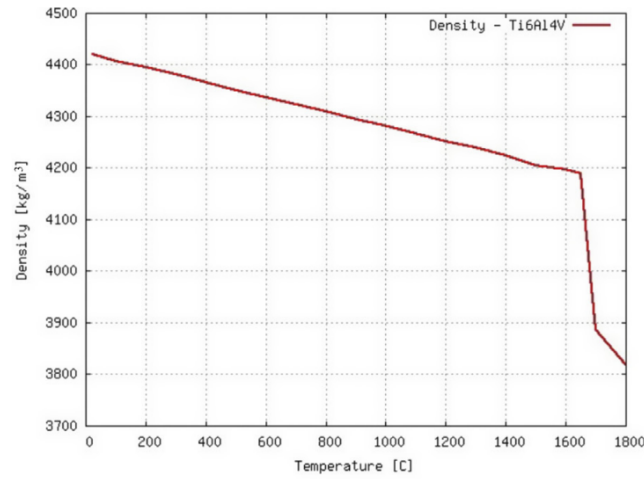


Figure 3.11: Density profile of Ti-6Al-4V used on the simulation [42].

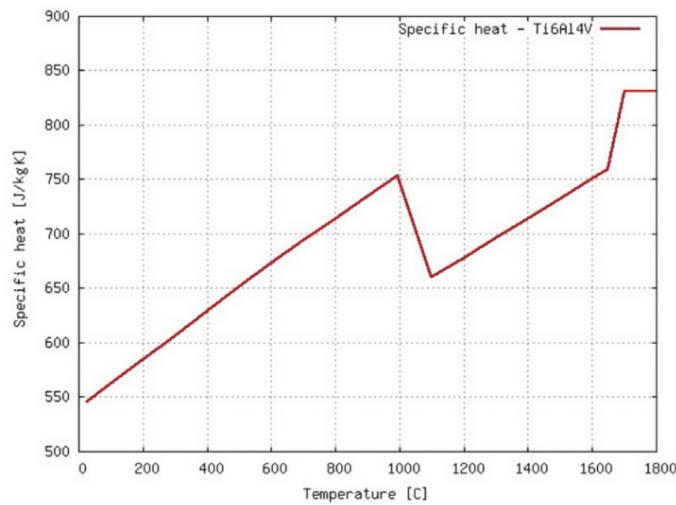


Figure 3.12: Specific heat profile of Ti-6Al-4V used on the simulation [42].

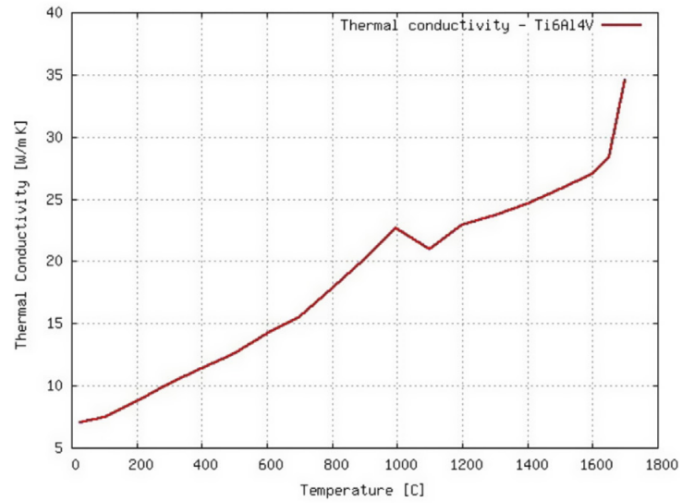


Figure 3.13: Thermal conductivity profile of Ti-6Al-4V used on the simulation [42].

The many steps that determine the simulation's temporal evolution are then implemented. The sum of all the step periods returns the overall simulation time, which must agree with the experimental deposition time if the additional final cooling time is disregarded.

Since the ABAQUS Model Change Feature necessitates that the newly active material attributes begin at zero and ramp up during the time step, as specified in Annex A. This requires adding a specific step with a very short step duration, which allows the activation of the next cell and the subsequent application of the thermal load, including convection and radiation.

In the following scheme, Figure 3.14, the activation method for a simulation with two distinct geometries as the experiment can be better understood.

The representation uses colors to help identify each step and geometry. Blue stands for the Deposition step and Green for the Activation step, where yellow represents "geometry 1" and orange represents "geometry 2".

In order to prepare the step module, it is required to give a minimum, a starting, and a maximum increment to ABAQUS to proceed. An increment is the interval of time between two successful simulation iterations. Whenever the simulation fails to converge for a given increment value, ABAQUS decreases the increment value by 1/4 and reattempts to solve the transient heat conduction equation. Alternatively, if convergence occurs smoothly, the subsequent step of ABAQUS often attempts to raise the increment value to accelerate computing speed. Initial and maximum increments for the activation stages match the step time. The minimum increment chosen was random. In this case, it was 10^{-15} s. If the simulation works properly, the minimum increment will never be attained. The beginning increment for the deposition steps is equal to 10^{-5} , a value always lower than the Δt_{cont} . The maximum increment equals the layer deposition time minus the Δt_{cont} .

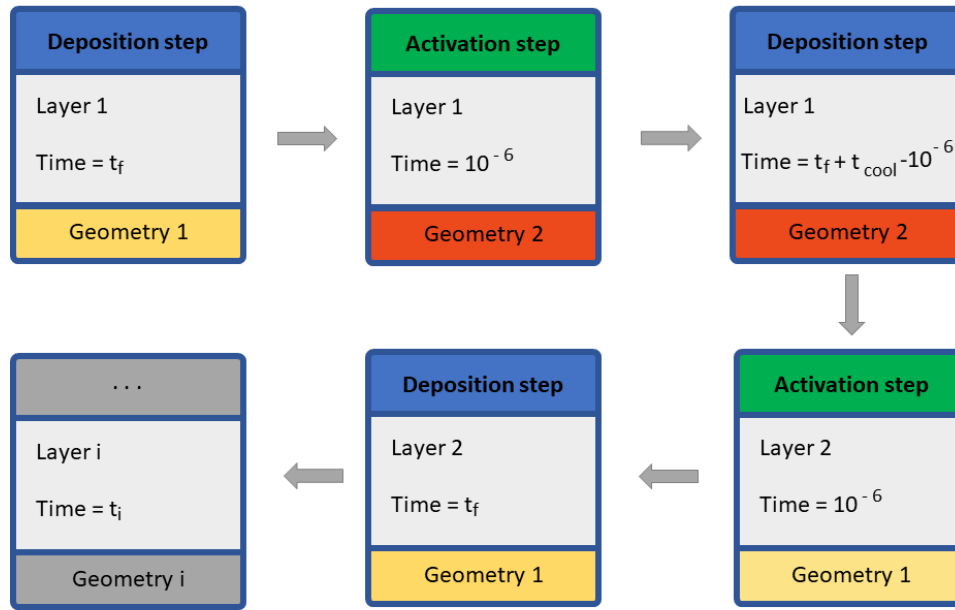


Figure 3.14: Schematic representation of activation/deposition method for two geometries on the same baseplate.

Once all the steps have been established, each thermal load is given. Heat body fluxes $\dot{Q}_V'''$ are given to the deposited layers. These loads are only active during that step time and deactivated soon after that.

Since we are using FH, a particular amplitude function is needed, as shown in Figure 3.15. The region underneath the function refers to the amount of volumetric energy placed in the layer. In the actual experiment, the input energy would be dispersed over deposition time, as seen on the right. Nevertheless, quick energy input is needed to surpass the melting point since we put the layer all at once.

The final step missing from the simulation setup is meshing, which is the discretization of the geometry in FEM elements. This is strongly geometry-dependent, and through the code, only for simple geometries, it is possible to specify the mesh and which heat transfer elements are desired for the analysis — further developed on the meshing process can be found in Section 3.3.3.

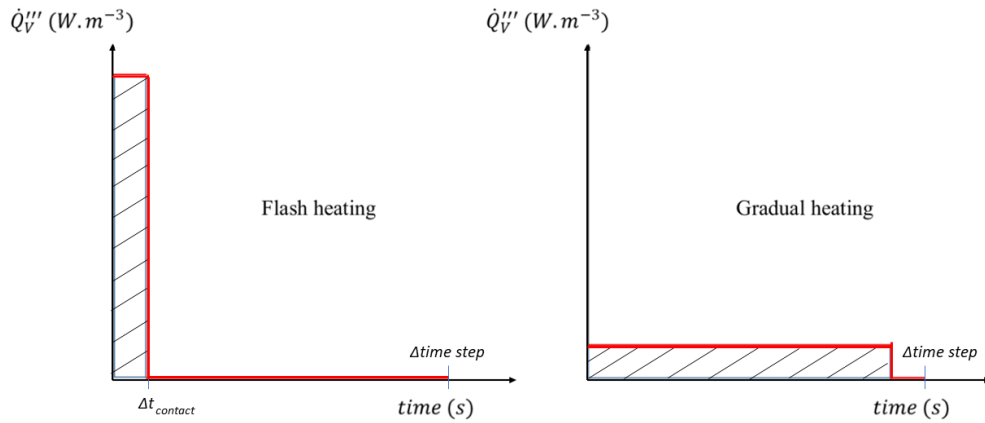


Figure 3.15: Amplitude function applied to thermal loads.

3.2.3 Validation of the thermal model

In the beginning, two geometries without overhangs were tested. However, there was not all the information needed to continue the calibration process. Therefore, further investigation was paused, and the focus changed to the geometry presented in this thesis. It is possible to find more detailed information regarding this initial work in Appendix A.

After it, two specimens were simultaneously simulated, as shown in Figure 3.16, but the iterative process was not moving too slow. Therefore, it was focused on only one specimen, the 50-length geometry.

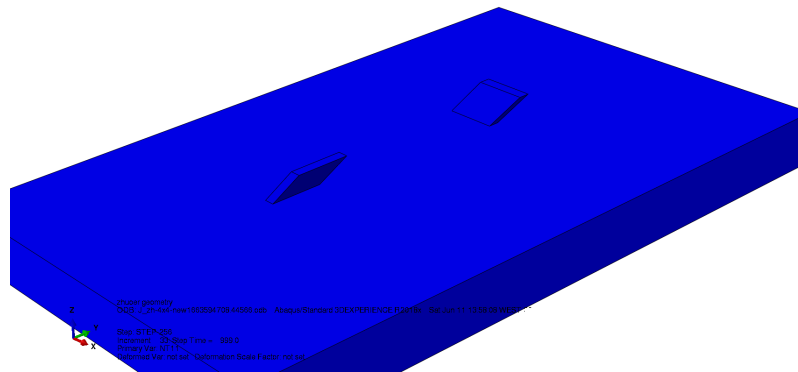


Figure 3.16: Initial CAD with the two specimens.

To validate the model, the idea is to extract some temperature-time curves for some specific nodes (sharing the same spot as the thermocouple measurements), in both the ABAQUS model and the experimental results and compare these for different values of powder convection and Δt_{cont} until a sufficiently good match is obtained. Fig. 3.17 shows the CAD model used for this validation simulation.

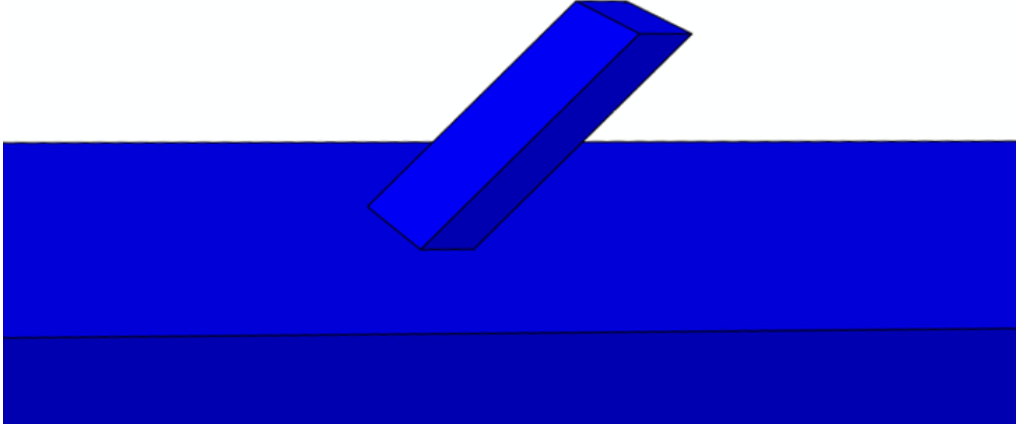


Figure 3.17: CAD view of the 50 millimeter specimen.

To assess the feasibility of the model, some statistical evaluations were made between the ABAQUS temperature-time curves and the experiment results. One of the statistical methods employed was the root-mean-square error (RMSE). This indicates the difference between the simulation-predicted temperature values and the experimental temperature values at the same time value:

$$RMSE [^{\circ}C] = \sqrt{\frac{\sum_{i=1}^N (T_{i,ABQ} - T_{i,EXP})^2}{N}} \quad (3.15)$$

Where $T_{i,ABQ}$ represents the temperature observed in the ABAQUS simulation, $T_{i,EXP}$ represents the temperature detected through the thermocouples, and N represents the number of time points gathered. As a result of different extraction frequencies, the two databases do not assess the temperature at the same instants in time. According to the RMSE definition, it is necessary to assess the temperature at the same values of t for both models, which necessitates a prior interpolation between the provided data points at desired equidistant values of t .

For a visual approach, some of the data was smoothed, to better see the average behavior. However, the smoothed data cannot be statistically analyzed on account of the carried error from the smoothing processes.

After obtaining a well-behaved model, we test the numerical method's capabilities to see if it can keep physical meaning when some of the parameters of the simulation change. Further detail in Section 3.3.4.

3.2.4 Solidification rates study

Based on what is mentioned in Section 2.1.8, the solidification rate influences the final product's microstructure. According to the literature, the solidification rate also varies with distance from the baseplate. As the thermal model provides estimations of the changes in temperature over time, this is adequate for evaluating some of these rates.

Then, two attempts are made to represent the different types of cooling rates. The final cooling rate extracted from the experience and the validated model will be analyzed together. If the thermal boundaries are correctly designed, they should have the same final slope since they extract the heat at similar rates.

Another attempt is to verify if the first cooling rate in the first layers is bigger than in the last layers. This should be true since there are no heat compensation and the thermal model start to suffer from heat accumulation. Figure 3.18 shows where the cooling rates were extracted on a $f_{lump} = 1$, on a layer-by-layer method.

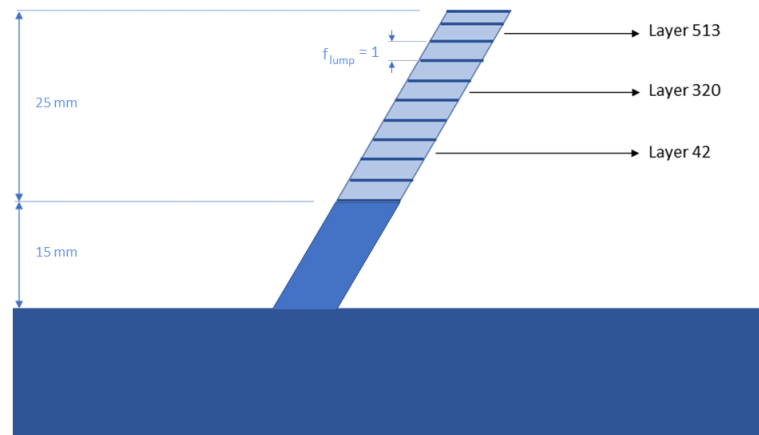


Figure 3.18: Schematic representation of the layers where it was extracted the cooling rates.

Therefore, it will be expected to see a faster cooling on the first built layers as well as lower peak temperature.

3.3 Simulation Details

3.3.1 Finite Element Method

FEM is a numerical solution that discretizes a continuum body or space into elements whose behavior can be explained using differential or integral equations. This can be applied to 1D, 2D, or 3D problems. Each element will have a set of end-point, also known as nodes. Some types of elements may also have some interior nodes. FEM also allows obtaining the behavior of a physical system in space and time. The interpolation functions obtain this for each element or node. The network of elements defining a body/space generates the so-called mesh. An element's size will vary, affecting the simulation's accuracy and convergence [44].

AM simulations gained a lot from previous welding field research since they share many phenomena. The most common use of FEM in AM is to study the effects caused by the thermal gradients. Normally, residual stresses and distortions. However, comparing LPBF to standard welding techniques, there will be a considerable difference concerning the way of adding material since the normal layer thickness in LPBF is around $50\ \mu\text{m}$. This change will increase the physical problem's complexity and computational cost [45, 20, 2].

Therefore, high fidelity AM simulation is still an ongoing field of research where the results take longer than the actual manufacturing process, which is already long compared with other metal manufacturing processes. Therefore, finding computationally efficient methods with reliable results is of the utmost importance [45, 35].

3.3.2 FEM in Heat transfer Problems

Problems involving heat transfer are governed primarily by the heat conduction equation. When examining steady-state, FEM modeling is conducted, considering that thermal equilibrium must be attained. FEM rearranges the equation for steady-state heat conduction as follows:

$$\nabla^2 T = 0 \rightarrow [K_{th}]\{T\} = \{r_Q\} \quad (3.16)$$

Where $[K_{th}]$ is the global thermal conductivity matrix, $\{r_Q\}$ is the external thermal load vector, and $\{T\}$ is the nodal temperature vector. For heat transfer concerns, investigating transient problems is crucial. In several applications, like this one, it is vital to know the temperature evolution throughout time, not only the ultimate steady-state. In MAM, for instance, a steady-state is not attained until some time after the end of manufacturing, when the component reaches room temperature. At this point, the temperature value is no longer of great importance. The expression for the 3D transient heat conduction equation is

$$k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \dot{Q}''' = \rho c_p \frac{\partial T}{\partial t} \quad (3.17)$$

where k is the conductivity, $\dot{Q}'''$ is the heat body flow, ρ is the density, and c_p is the constant-pressure specific heat capacity. Here, the heat conduction equation is displayed directly in three

dimensions. This is because the sole nodal degree of freedom present in both 1D and 3D situations is temperature.

Equation 3.17 is derived using FEM to provide the following system:

$$[C_{th}] \{\dot{T}\} + [K_{th}]\{T\} = \{r_Q\} \quad (3.18)$$

Regarding the preceding formulation, a new term on the transient nature of the system is added. $[C_{th}]$ is the thermal capacity matrix, and $\{\dot{T}\}$ is the rate of change in temperature (each component is dT_i/dt). This can only be analyzed if the temperature for two consecutive time steps is known. There are two potential options: an explicit approach that utilizes the temperatures from the previous time step and an implicit way that uses the temperature from the current time step. In general, commercial FEM software favors implicit approaches since they are typically unconditionally stable. ABAQUS, the commercial program utilized for this research, uses an implicit way to solve this problem. The employed approach is the reverse Euler formula:

$$T_{t+\Delta t} = T_t + \Delta t \cdot f(t + \Delta t, T_{t+\Delta t}) \quad (3.19)$$

In the first iteration, $T_{t+\Delta t}$ is predicted and placed on the right to determine the new $T_{t+\Delta t}$. This is repeated until the new temperature value for every node converges. Each node's function $f(t, T)$ is given by the system of equations 3.18. Heat transfer in FEM typically only considers conduction (governed by Fourier's law) as a transmission technique. This is a decent approximation for analyzing solid substances. Other processes, like convection, should not be ignored when considering fluids, which happens on a meso and micro scale in AM processes.

3.3.3 Finite Element Mesh

More specifically, a 3D 8-node linear brick element was employed as heat transfer elements DC3D8. The element sizes directly influence the printing simulation's results. Therefore, a more refined mesh will translate to better-predicted temperatures. However, it increases the computational cost, which is not what the desired effect.

Mesh refinement is the process of determining what dimension the mesh size should have to have minimal impact on the numerical output. As a rule, a finer mesh yields a more reliable output, but it also has the disadvantage of being more difficult to compute.

Suppose a movable heat source was used instead of a FH method. In that case, the specified mesh size must be smaller than the laser beam spot size to obtain an accurate local thermal response, especially to capture the peak temperature distribution. However, they also increase the computational load to a point out of hand [42].

The chosen Mesh is shown in Figure 3.19. This is composed of 801 580 Elements and 901 413 Nodes. There is a set of partitions in order to facilitate the meshing task.

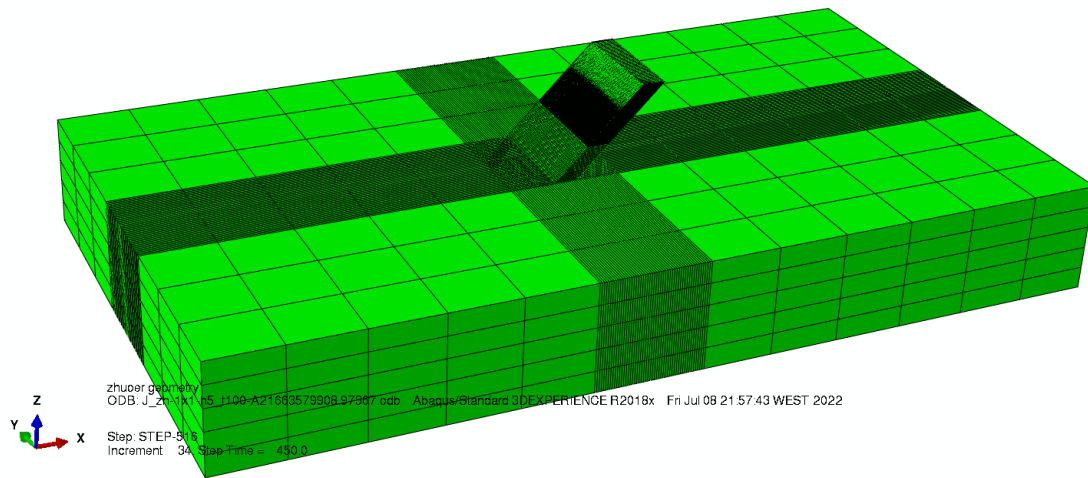


Figure 3.19: A geral overview of the model mesh.

In the development of the model, it made sense not to have the exact size of the mesh on all of the geometry. Therefore, different edge sizes were assumed. In order to acquire correct findings in an acceptable computational time, it followed the rule that the place had the lowest thermal gradients should have a coarser mesh than the places where the heating occurs, for example.

The first step is dividing the model into groups: Baseplate, Pre-build, and Upper build. In Figure 3.20, it is possible to see the partition alloying to cut part of the baseplate into a squared form where the pre-build is going to settle in order to ease the meshing.

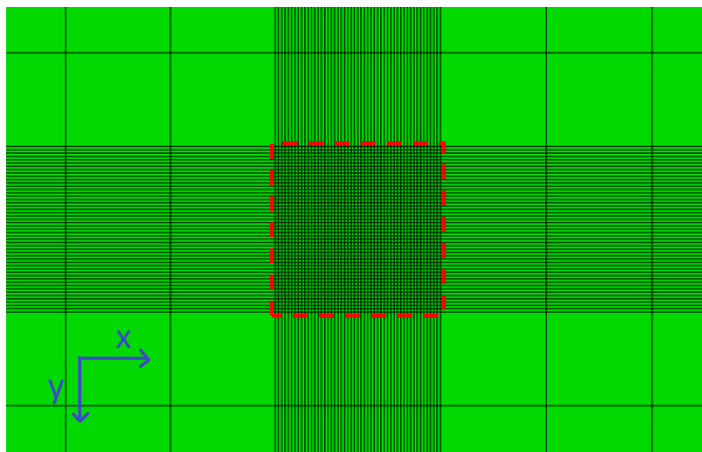


Figure 3.20: Closer look into the four partitions occurred on the baseplate.

The baseplate is seeded with a coarse mesh of 10mm on the height (ZZ) and 40 millimeters on the plane XY as seen in Figure 3.21.

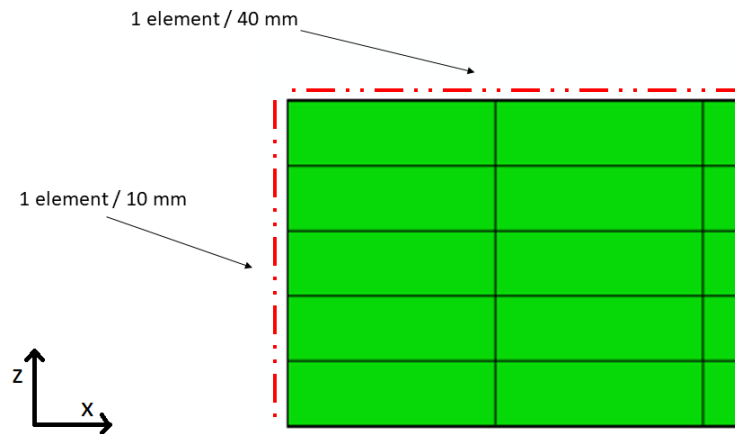


Figure 3.21: Closer look into the Baseplate meshing.

Then, the mesh on Pre-build height and Upper build height have the most important impact since when the heat body flux actuates, the most considerable percentage of the heat is extracted through conduction to the baseplate. In the case of the Upper build meshing height, it was also possible to give the input in elements per cell instead of element per distance. This feature was more important when the number of lumped layers was higher. The upper build meshed was seeded with three elements per new activated layer, and the Pre-build mesh had one element per 1 millimeter. Figure 3.22 shows in greater detail the meshing mechanism.

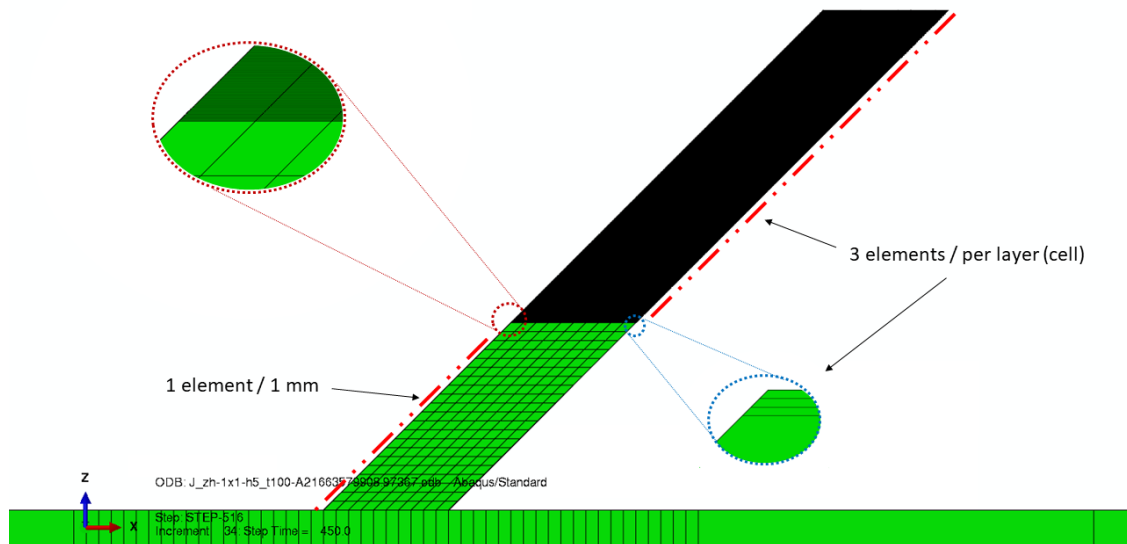


Figure 3.22: Closer look into pre-build and upper-build meshing.

Table 3.3: Coordinate of nodes chosen to represent the thermocouples.

Name	Node	x [m]	y [m]	z [m]
50 - Up	67 101	- 0. 005 000	- 0. 104 000	0. 065 000
50 - Down	67 045	0. 005 000	- 0. 104 000	0. 065 000

All the following simulations try to preserve the meshing details from the validated model, except for the lumping analyses where there are slight fluctuations. The further tests are conducted:

- Convection coefficient of the powder, h_{powder} ;
- Bottom temperature, T_{bottom} ;
- Layers in the lump, f_{lump} ;
- Overhang angle, α .

Figure 3.25 shows a schematic view of the different parameters tested on simulation parametric analysis. Another simulation output that was carefully studied is the simulation time. By maintaining the same meshing pattern, its fluctuation will have a more significant impact when applying a different f_{lump} .

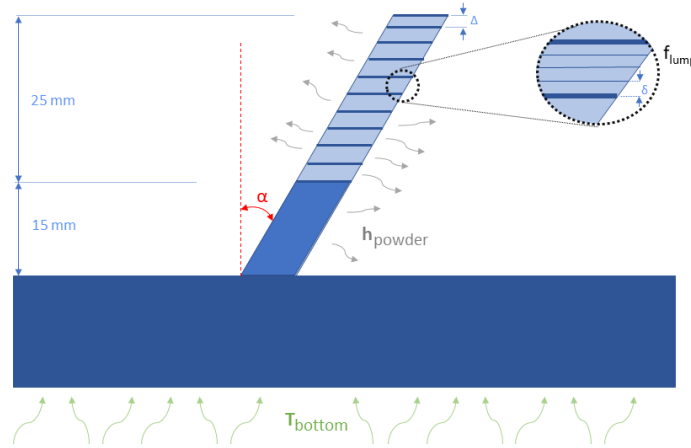


Figure 3.25: Schematic representation of the parameters studied.

Change of boundary conditions - A & B

In the first two studies, A and B, we change some boundary conditions to understand their effect on the simulated results. In simulation A, the primary purpose is to understand which is the

thermal behavior of the Down and Up surfaces when changing the h_{powder} while maintaining the $T_{sink} = 100$ °C. While in simulation B, the main purpose is to understand the thermal behavior of the Down and Up surfaces when changing the T_{bottom} . The following table shows the different values tested:

Table 3.4: Parametric study A and B, chosen parameters of h_{powder} and T_{bottom} .

Name	h_{powder} [$Wm^{-2}K^{-1}$]	T_{bottom} [°C]
A1	1	100
A2 / B3	5	100
A3	15	100
B2	5	75
B1	5	50

It is expected to obtain a higher average temperature at A1 rather than A3. Nevertheless, the slope behavior on the changing of the h_{powder} is more interesting to see. While by changing the T_{bottom} while maintaining the same h_{powder} , it is expected to obtain a lower average temperature at B1 rather than B3. The lower the temperature, the bigger the thermal gradients. This will prove the necessity of pre-heating on the substrate to decrease the residual stress potential in order to achieve a higher average temperature during the process.

Change of layers in the lump - C

On the following studies, we start to play with some simulation parameters. The main purpose of simulation C is to understand the simulation behavior when changing the f_{lump} while maintaining the rest of the process parameters. The following table shows the different values tested:

Table 3.5: Parametric study C, chosen parameters of f_{lump} .

Name	f_{lump}
C1	1
C2	2
C3	4
C4	8
C5	16

It is expected to obtain faster simulations on the biggest lumps. Therefore the simulation time of C5 must be lower than C1. Study C is also expected to have more significant fluctuations in the results since the Δt_{cont} is constant between simulations. While the Step time and the new volume activated have a bigger mass.

Change of the overhang angle - E

In order to not confuse the study D with the "D"own surface, it was decided to jump a letter. Therefore in study E, the main purpose is to understand the thermal behavior when changing the α in which the overhang lays. The following table shows the different values tested:

Table 3.6: Parametric study E, chosen parameters of α .

Name	α [°]
E1	0
E2	22,5
E3	45
E4	67,5

In this study was necessary to apply different CAD models since the python script does not create the geometry. Therefore, the following Figures 3.26 shows the new 3D CAD models.

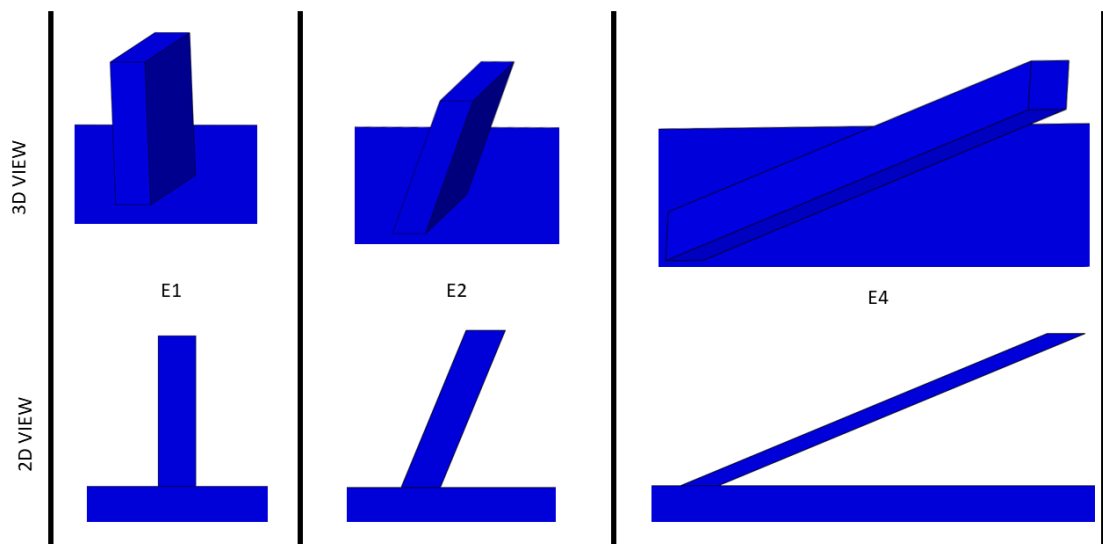


Figure 3.26: New CAD models for study E with different α . From left to the right, E1 = 0°, E2 = 22,5°, and E4 = 67,5°.

It is expected that E1 does not present any difference between the measurements Up and Down. In this study, it is also expected to be the one with the minor effect of heat accumulation. E4 should present the most considerable temperatures. Typically, components with such angles must have structural supports to keep the part quality.

3.3.5 MATLAB interpreter

Another important component of this thesis is the developing of a mathematical code to analyze and process *in-situ* measurements taken with photo sensors and cross the information of the simulation results. The program chosen was MATLAB since it is the perfect tool to deal with big data sets. The *in-situ* information came from the bridge specimen known in the AM scientific community. The CAD model can be found in Figure 3.27.

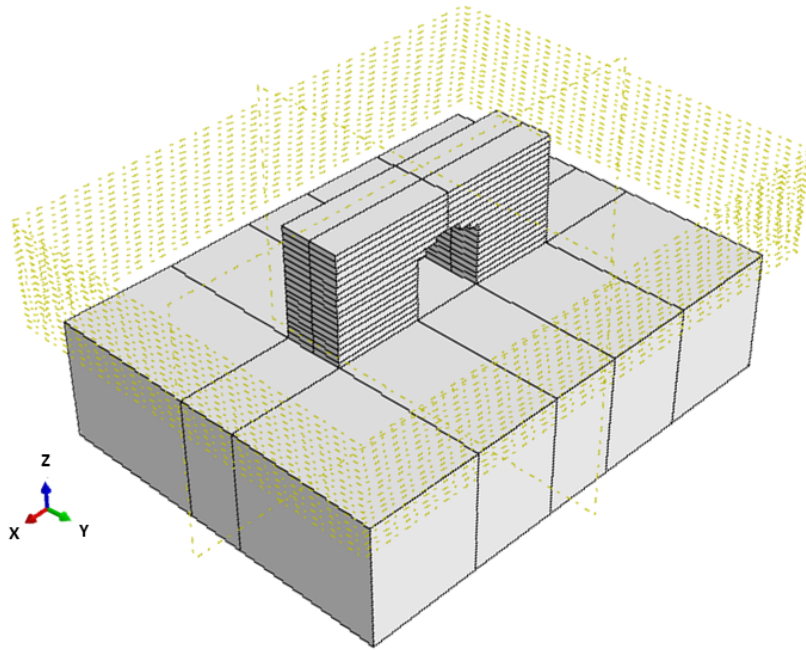


Figure 3.27: 3D CAD view of the Bridge model.

The *in-situ* information is obtained with a photodiode camera. Photodiodes are a type of diode that turns the energy of light into electricity. Their operation is the exact reverse of LEDs, likewise diodes that transform electrical energy into light energy. Photodiodes can also be used to measure the intensity of light.

Figure 3.28 shows an expected output data of a photodiode. Temporal dependent information with the variation of intensity along the time.

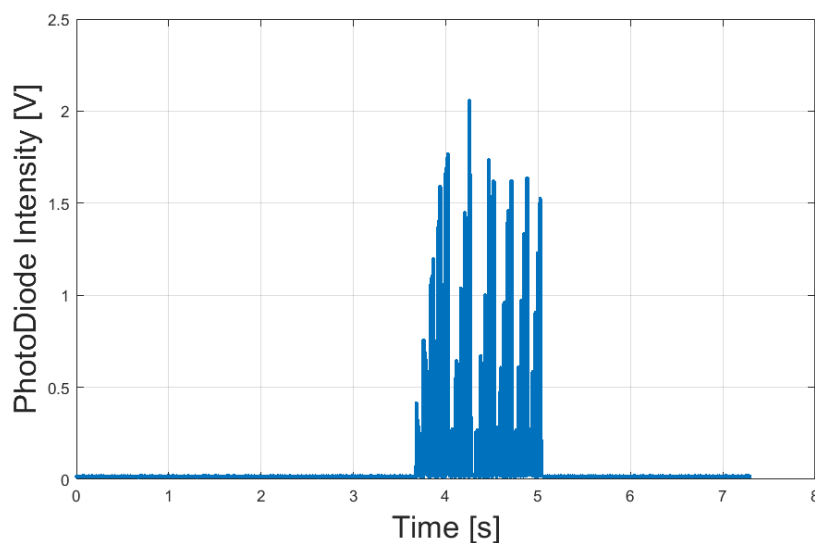


Figure 3.28: Photodiode data plot example.

However, in AM, we know the exact speed of the laser. Therefore, creating an algorithm that saves the intensity value in the correct position is possible. In other words, knowing the scanning pattern in AM makes it possible to turn a temporal variable into a temporal-spatial variable. With this concept in mind, there were made *in-situ* measurements of the Bridge specimen manufacturing. The information was processed in 1680×1680 matrix pixels, where each cell had a range of 64-bits. This could be converted to an image that could be easily stored and read in the opposite direction. This would save a lot of hardware space since *in-situ* data is known for producing enormous amounts of information in a short time. Photodiodes have a frequency of 100 kHz, compared with the data-logger used in the experiment in Section 3.1 of 1 Hz. If the data-logger had a 64-bits register capacity, it would mean that the photo-sensor results would be approximately 100 000 bigger. Therefore, saving temperature values on a black and white scale brings many possibilities that must be explored.

Nevertheless, the code developed here has the capacity to extract all the node temperature information along the time from the simulation results. This could be used to cross information from the *in-situ* monitoring and the simulation to create a digital twin.

A digital twin is a virtual replica created to reflect an actual thing identically. The object under study, such as an AM-manufactured component, is furnished with numerous sensors linked to the process. These sensors generate information regarding the performance of the physical device, including gas flow, temperature, melting pool size, and more. This information is then transmitted to a system for processing and applied to the digital copy.

The digital twin technique can influence the additive manufacturing process by optimizing the process parameters, detecting and monitoring process problems, lowering the computing burden for multi-scale modeling, and managing the enormous amount of *in-situ* sensor data [46]. Figure 3.29 shows a schematic representation of a digital twin applied to MAM.

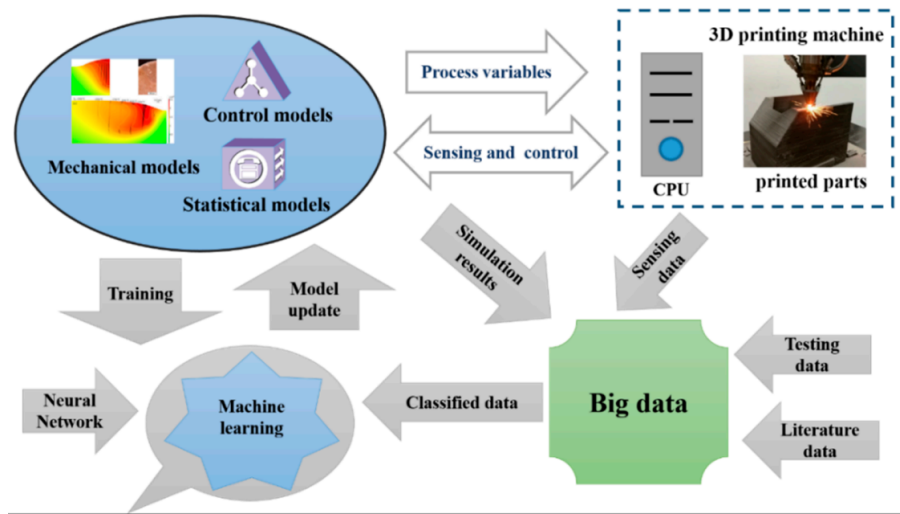


Figure 3.29: Logical representation of the digital twin for additive manufacturing [46].

After that, with the code given by Dr.Venkata Karthik Nadimpalli, it was possible to generate visual information of the manufactured bridge model with *in-situ* information. In Figure 3.30 and Figure 3.31, it is possible to see two different kinds of representation.

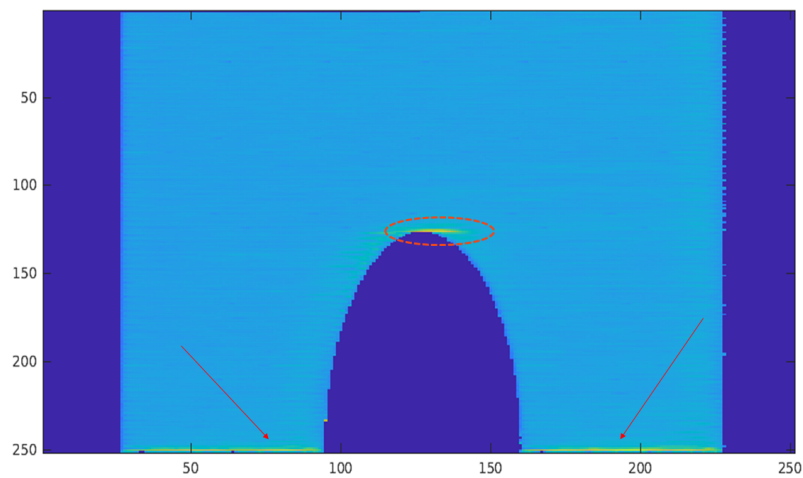


Figure 3.30: Bridge *in-situ* colored representation with cold and hotspots (Shared by Dr. Venkata).

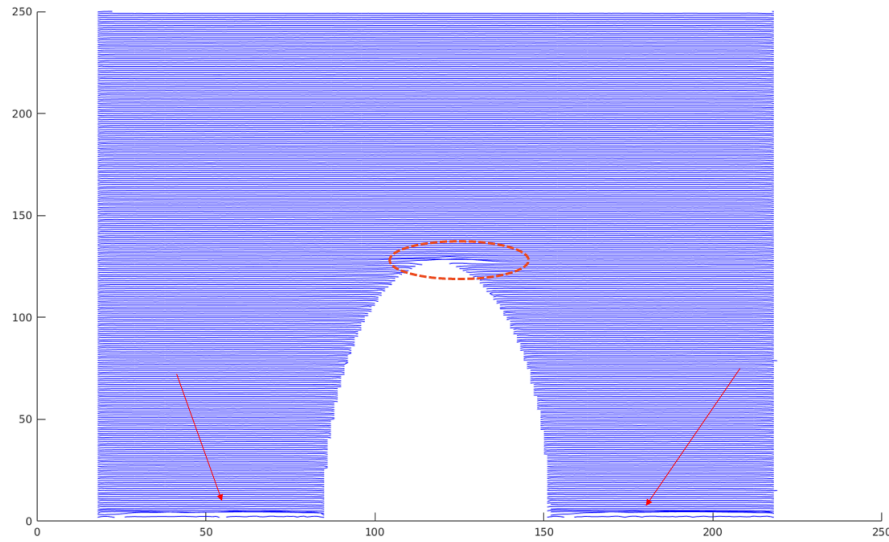


Figure 3.31: Bridge *in-situ* line deviation representation with cold and hotspots (Shared by Dr. Venkata).

Both are the same input of pixelized intensity voltage acquired by the *in-situ* photodiode. Nevertheless, on the first one, it is shown in colored representation, where the lighter the color means that the temperature at that point is higher than the average of the layer's temperature. The opposite is also true. The darker, the lower the temperature at that point compared with the same layer. The second approach, instead of a color method, opted for a colorblind methodology, where each line represents a different layer where, for layer 200, if the value of the line is 200, it means that that point shares the average of the layer. However, a higher value means that the temperature at that point overpasses the average and vice-versa.

With this type of visualization, it is possible to see that on the overhang of the bridge, on the first layer of it, we can see the rise of a hotspot which can mean dross formation or keyhole porosity. Furthermore, the exciting fact about this region is that it is shifted from the center of the figure, which might mean that the hotspots are scanning pattern-dependent.

Nevertheless, the same visualization techniques were applied to the simulation results instead of using the *in-situ* monitoring data.

However, one of the handicaps of the actual python script is the inability to measure the area of the printing layer through the CAD. Therefore, the area needed to be either constant for each cell or inputted for each layer, which will reduce the applicability of the script on more complex geometries. So, instead of applying this methodology to the Bridge model, in the last instant, it was applied it to a smaller scale of the 50 - specimens used in this work, with a $f_{lump} = 50$ and a coarser mesh. In order to run the code, to read the Simulation data and cross it after. Files with more than 500 Gb were needed. Moreover, further developments were cut off until a better way to store the simulation information is implemented in this code.

Figure 3.32 and Figure 3.33 shows the same methodology applied to the 50-specimen of our experiment.

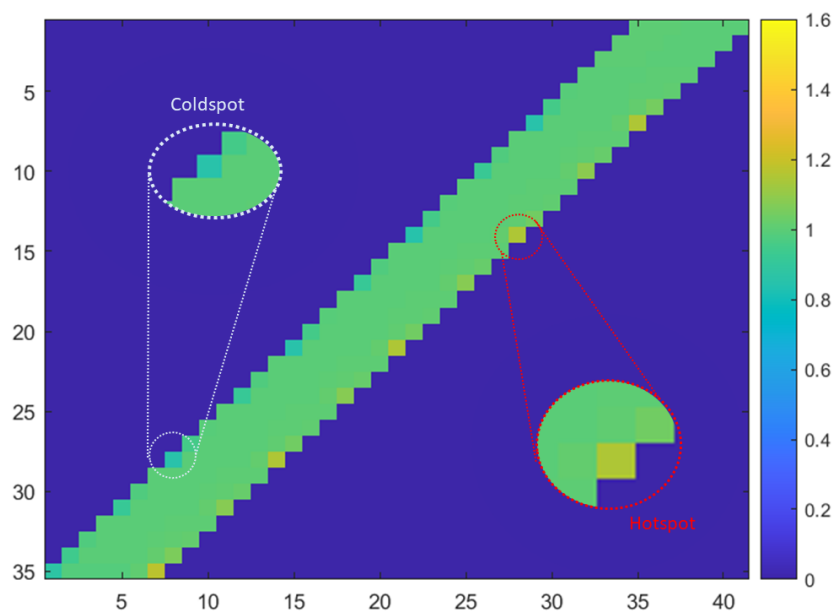


Figure 3.32: Color representation of the 50 millimeter specimen simulation with the cold and hotspots.

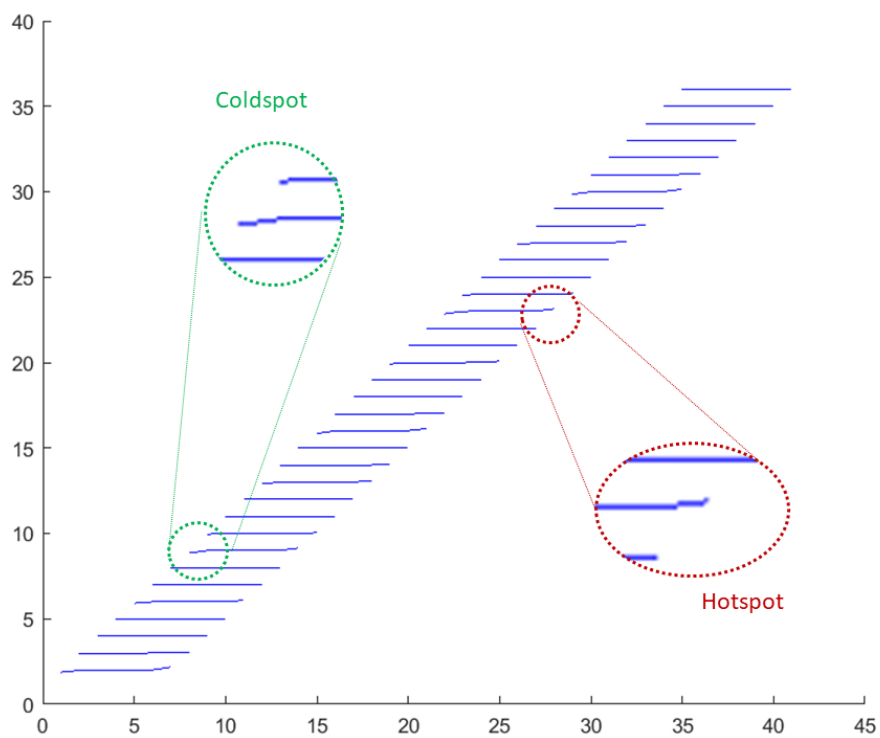


Figure 3.33: Line deviation representation of the 50 millimeter specimen simulation with the cold and hotspots.

On the colored approach, the sensibility of the color bar has currently no physical meaning.

However, it is achievable to see the expected differences between the Up and Down surfaces. While in Figure 3.33, it is already possible to verify a slight deviation in each line at the beginning and end of each line. As expected, the left part of the line approximates to the line under it. In contrast, the right part of the line approximates to the line on top, meaning that the probability of a hotspot here is higher than in the opposite part.

An important note concerning the *in-situ* visualization is that we can only see the intensity of a specific point at the moment of its deposition. When a new layer comes, it is impossible to capture the interaction between the new layer and the previous one.

Chapter 4

Results and Discussion

In this Chapter, the experimental results are shown, as well as the numerical simulations described in Chapter 3 are presented and discussed in further detail.

4.1 Experimental Results

The thermocouples outputs are shown here in Figure 4.1. Important to notice, that the pre-heating system was turned on before the data recorded. Around 500 seconds, the first scan (pre-exposure) is made in order to process any residual dust that stayed on top of the specimens when replacing the powder.

In Figure 4.2, it is possible to see with more detail the pre-heating surfaces data. The 50-Down skin output and 10-Down skin output present the same average value along the time. During the phase of baseplate re-heating to 100 °C, none of the four thermocouples channels reached 100 °C in two hours' time, while upskin surfaces reached slightly higher equilibrium temperature. Channels at the down-skin surfaces showed much sharper peaks compared to those at the upskin surfaces. The temperature exhibits fluctuations as the build re-continued. The local fluctuations in temperature vanished with time and the temperature at the four channels exhibited a steady decline afterwards. The stabilised temperature range is determined by the heat transfer condition experienced by the respective channel. It is possible to verify that overhangs (downskin channels) are prone to the issue of over-heating as heat are easily captured and accumulated due to the thermo-insulating effect of powder and lack of heat conduction pathways.

Also, one interesting result, is the temperature difference in between the Up and Down surface, of each specimen seen in Figure 4.3. However, this difference cannot give us conclusions yet, since the only thing that it is maintained in between geometries is the volume and cross-section and not the length or the width. Therefore, it is impossible to wrap up for example an idea that the lower the thickness the bigger the temperature difference.

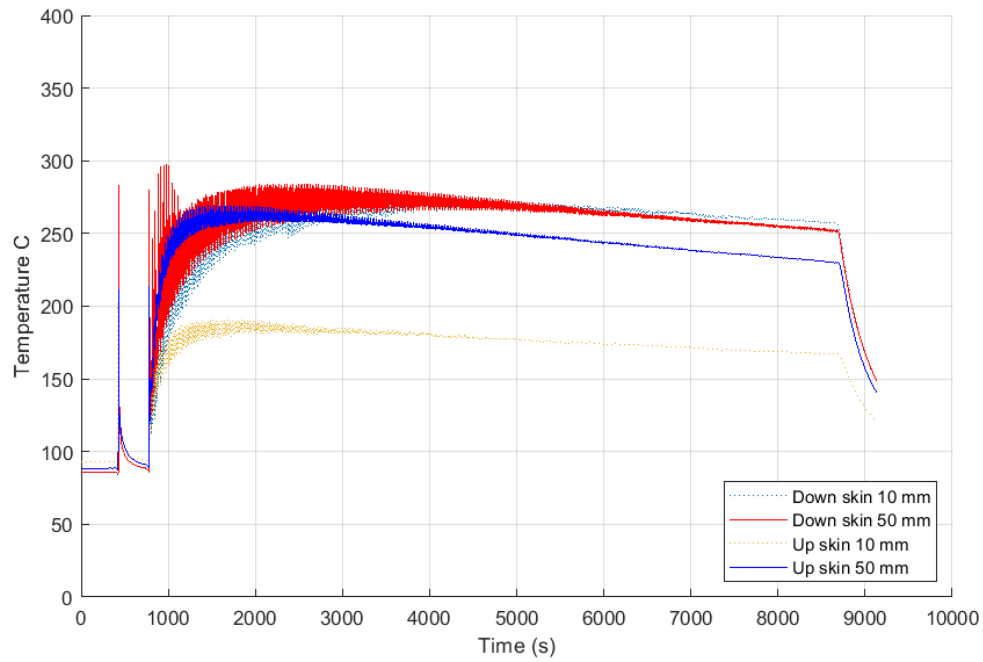


Figure 4.1: Temperature profile recorded by thermocouples fixed on Up skin and Down skin surfaces of both oblique prism specimens.

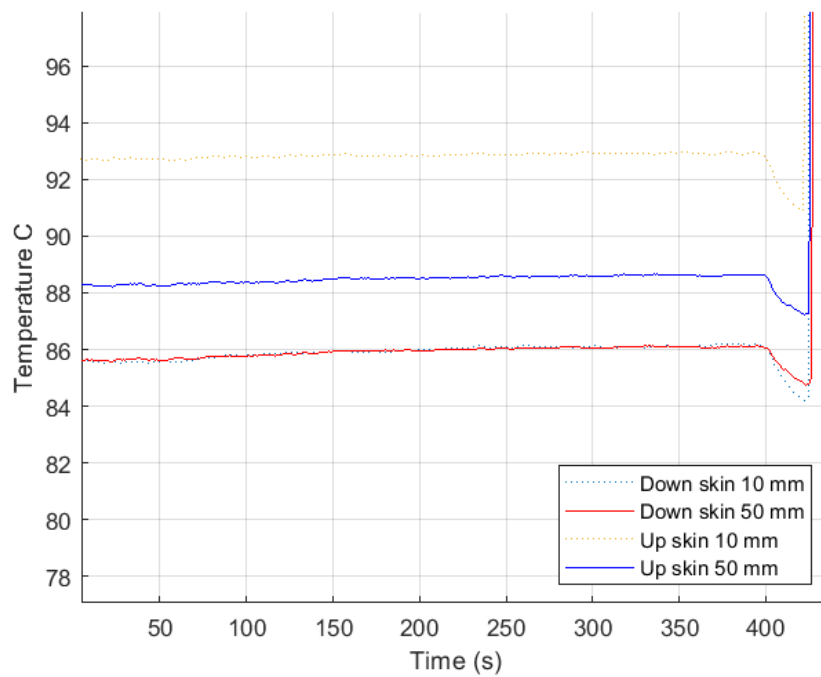


Figure 4.2: Temperature profile of the pre-heating right before the pre-exposure.

For the following numerical validation. Only the data shown at Figure 4.4 is used to calibrate the model. This is taken from the first moment it starts the process, to 500 seconds after the laser has stopped.

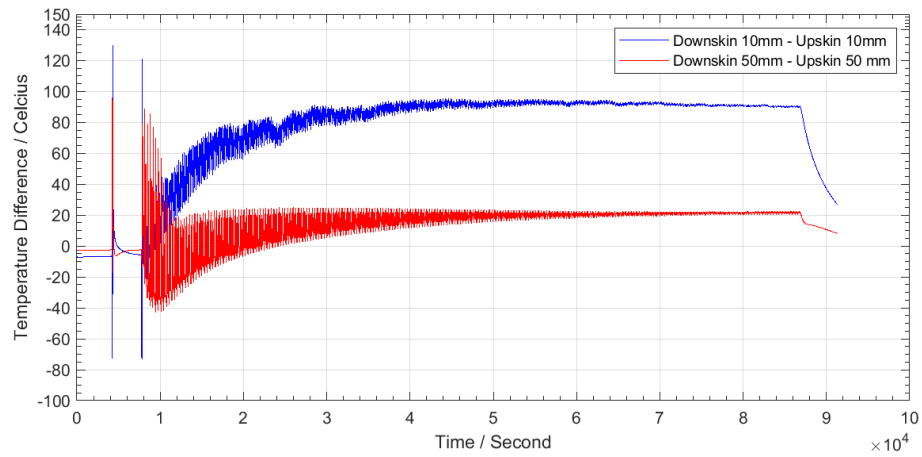


Figure 4.3: Temperature difference between Upskin and Downskin surfaces.

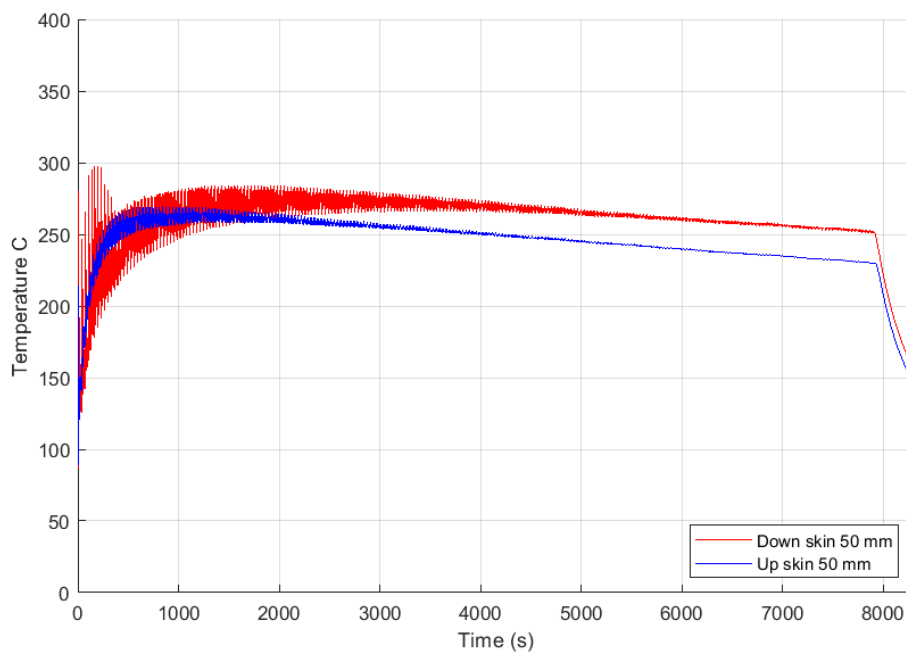


Figure 4.4: Temperature profile of the 50 mm specimen.

4.2 Numerical Results

Different subsections are discussed here, starting with the validation proof and after simulation parametric studies that test the numerical modeling reliability.

4.2.1 Validation of the thermal model

The thermal model is successfully validated while using a body heat flux of $\dot{Q}_V''' = 3,09598 \times 10^{11} \text{ W/m}^3$ and a contact time of $\Delta t_{cont} = 5 \times 10^{-2} \text{ s}$. With these settings, the energy input in a single layer is 375 J. This well-behaving model was obtained for such geometry when the absorptivity is equal to $\eta = 0,45$. A powder convection of $h_{powder} = 5 [\text{Wm}^{-2}\text{K}^{-1}]$ and sink temperature of $T_{sink} = 100 \text{ }^\circ\text{C}$. The bottom boundary had a constant temperature of $T_{bottom} = 100 \text{ }^\circ\text{C}$ while the radiation boundary of a new deposited layer had a emissivity of $\varepsilon = 0,4$ and a room temperature of $T_{amb} = 35 \text{ }^\circ\text{C}$.

The results from the thermal validation are given in Figure 4.5 and Figure 4.6. It is possible to see a comparison with the experimental values of Downskin and Upskin temperatures along the manufacturing process.

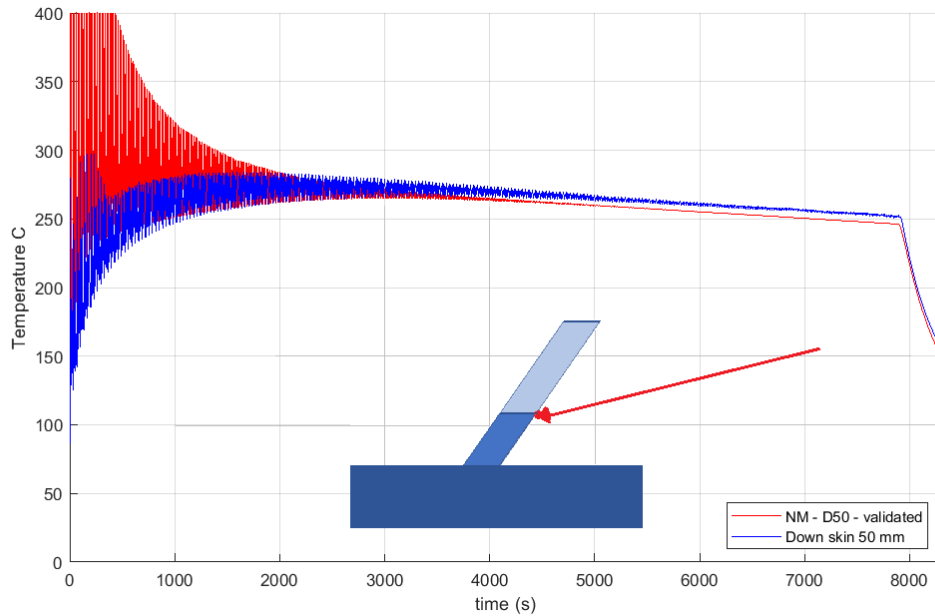


Figure 4.5: Temperature profile comparison between the experimental temperature Downskin (Blue) and the simulated temperature Down (D50 - Red).

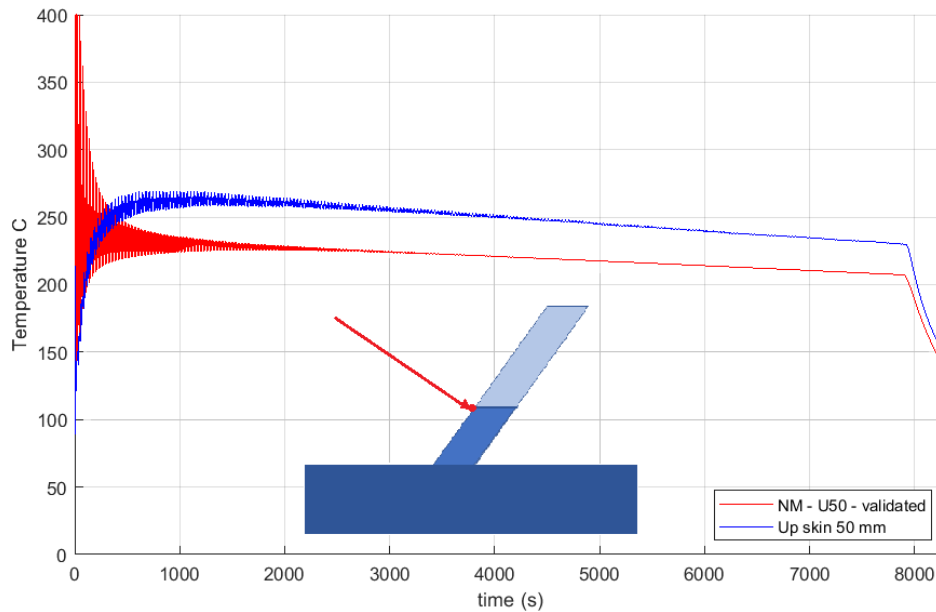


Figure 4.6: Temperature profile comparison between the experimental temperature Upskin (Blue) and the simulated temperature Up (U50 - Red).

The Figures 4.5 and 4.6 show a better match between the Down surface simulation (D50 - Red) and the Experimental (Blue). While in the Upskin results, it is possible to see that the agreement is not as straightforward as the Down surface. Both simulations underestimate the experiment temperatures. This can be due to ignoring the powder domain or from extracting too much heat from the piece, or even an interpolation problem, where some heat can disappear due to the overshoot of the temperature differences.

For the validation results, the RMSE method was applied. The RMSE of the Down surface validation is 24,8 °C and 44,3 °C for the Up surface. However, the simulation results show the same behavior as other research studies where the first layers have a significant oscillation [42]. This can have a considerable impact on their evaluation. Therefore, if we take out the first 1000 seconds of the simulation to better analyze, the RMSE values come to 11,8 °C and 46,8 °C, respectively. The Down surface simulation gets 52,5% closer to the reference value, and the Up surface gets 5,6% farther. However, if a visual evaluation is made of these temperature profiles, extreme fluctuation can obstruct the visualization of the experimental and simulated results. Therefore, it was applied a Savitzky-Golay finite impulse response (FIR) smoothing filter of *polynomial order 4* to smooth the data when we wanted to make it more clear to see. Therefore, Figure 4.7 presents the simulation results smoothed by the Savitzky-Golay method. This data smoothing will prove helpful in a further Section of this Chapter.

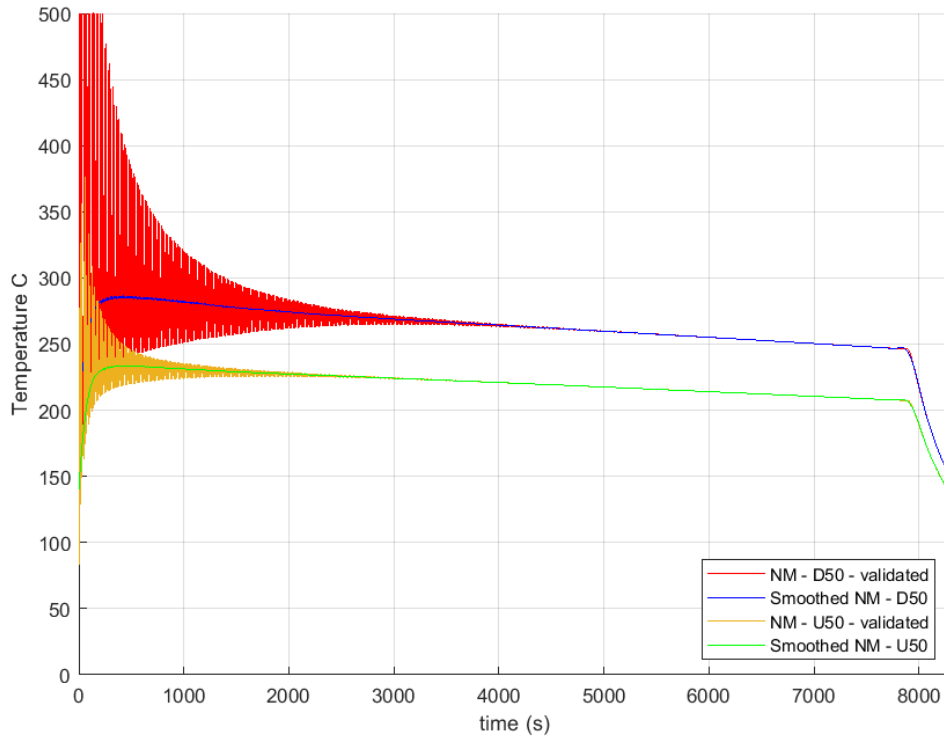


Figure 4.7: Temperature profile from the simulations with their respective smoothed profile by Savitzky-Golay method.

If there were modeling of the powder bed, it would be possible to detect a higher temperature on the powder-geometry interface since the temperature on the interface, solid-solid, would have higher conduction, hence dissipating more heat. However, this validation capture the general motion of the temperature build-up that stabilises at about 2000 seconds after the start of the manufacturing process. Afterwards, the temperature at the thermocouples decreases slowly until the end of the printing stage, when it drops until cooling down to the initial temperature.

4.2.2 Cooling rate study of the thermal model

In the following Figure 4.8, it is possible to see a similarity in the final cooldown, which is a good sign of thermal boundaries not being too different from the real ones. At least when behaving at lower temperatures.

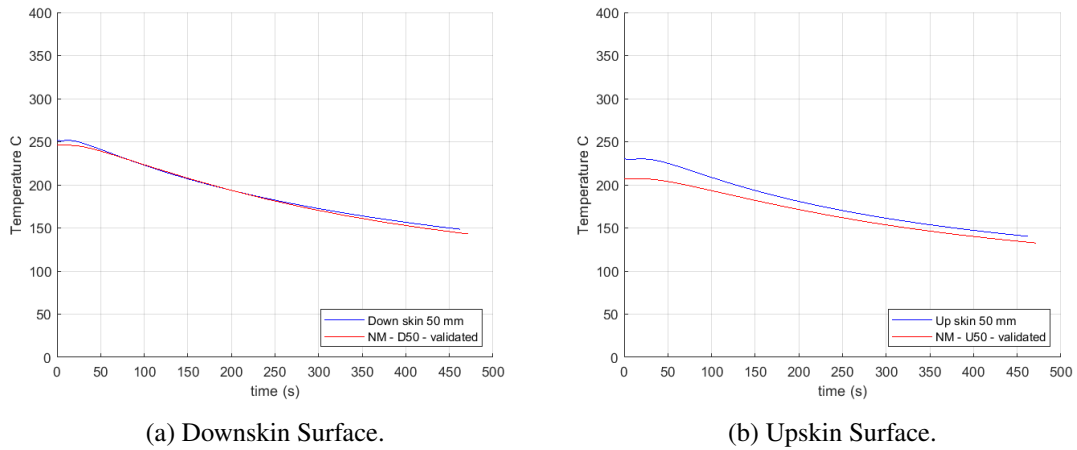


Figure 4.8: Temperature profile comparison of the final cooldown between the experimental temperature (Blue) and the simulated temperature (Red).

After, it is explored the changing behavior of the cooling rate along the manufacturing process. Hence, Figure 4.9 is shown the cooldown of three different layers during the first activation of each one from which the cooling rates can be evaluated.

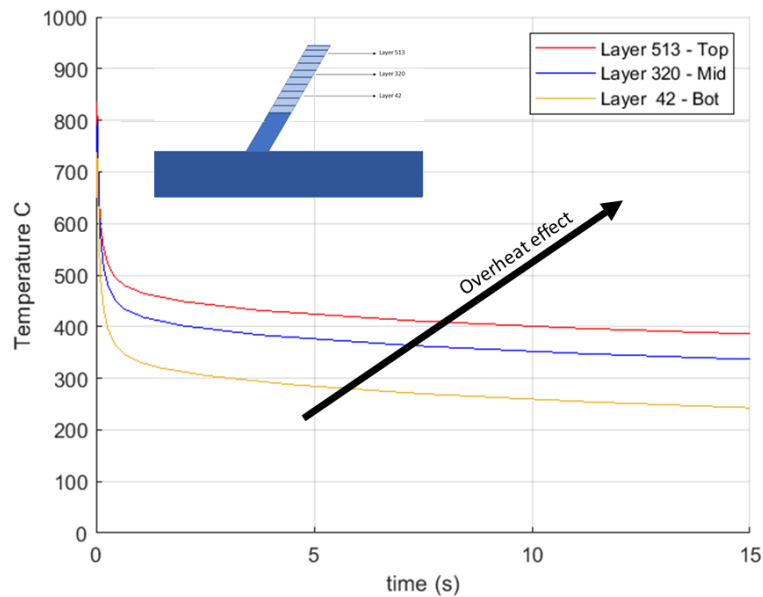


Figure 4.9: Temperature profile comparison of the first cooldown of different layers along the manufacturing process.

Different cooling rates are detected when increasing the distance from the baseplate. The higher the build, the greater the average temperature found. This proves the existence of overheating effect. The overheat effect is noticed when thermal energy input is not carried to the baseplate rapidly enough, resulting in localized overheating or heat buildup—overheating causes surface

flaws, such as balling and dross production, that degrade the quality of produced components [24]. In addition, local overheating can harm microstructural development, which significantly affects the final physical qualities and can lead to build failure. Overheating also considerably adds to residual stresses that cause component deformation [47].

In order to prevent local overheating, it is necessary to take precautions during the design and process planning phases [47]. Therefore, this numerical modeling can prove helpful in detecting regions or components that will suffer overheating with a particular set of parameters.

After the validation, an arrangement of tests are performed to study the usability of the numerical modeling and its reliability.

One interesting factor that is evaluated is the time needed to run this simulation. One goal would be to have a low time consumption to make it feasible to implement in an industrial context, where a feedback loop could be created. Since the number of thermal boundaries and f_{lump} have the most significant impact on simulations time, we examine more carefully the times in study C since it was a study of the behavior on the f_{lump} . In contrast, all the studies performed kept the same number of thermal boundaries.

4.2.3 Change of convection coefficient of the powder - A

In the following Subchapter, a quality analysis of the numerical modeling is performed, where one parameter is changed into the modeling to see if they behave as expected. This type of study can also take the name of the parametric study. The first parameter tested is the convection coefficient that emulates the powder, h_{powder} . In the following table, it is possible to see the chosen values of h_{powder} while maintaining a T_{sink} equal to 100 °C, the temperature chosen, in order to share the same temperature as the baseplate.

Table 4.1: Parametric study A, chosen parameters of h_{powder}

Name	h_{powder} [$Wm^{-2}K^{-1}$]
A1	1
A2	5
A3	15

In this study, A2 shares the same parameters as the validated simulation shown in Section 4.2.1. To make it easier to evoke that validated simulation, the rest of the document will take the name of A2.

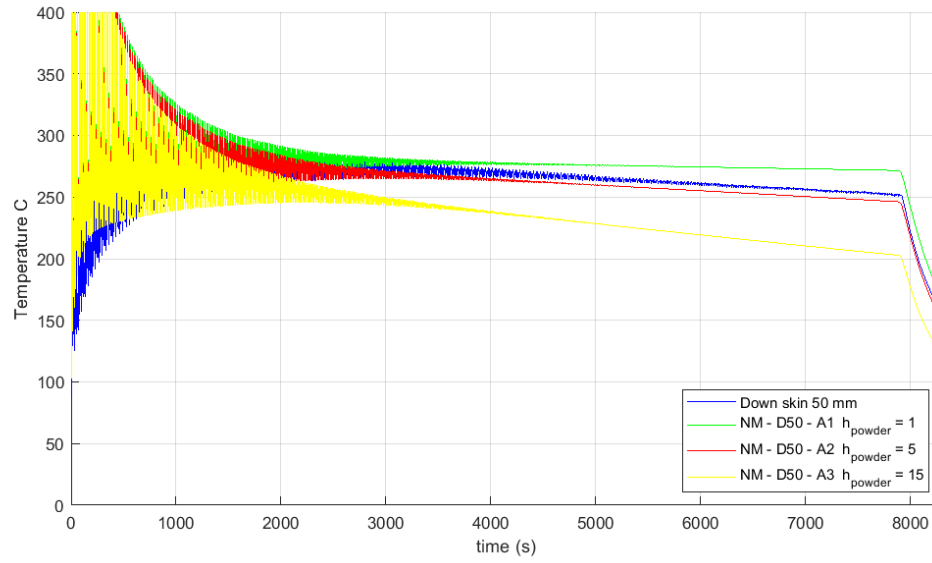


Figure 4.10: Temperature profile comparison of study A, between the experimental temperature Downskin (Blue) and the simulated temperatures.

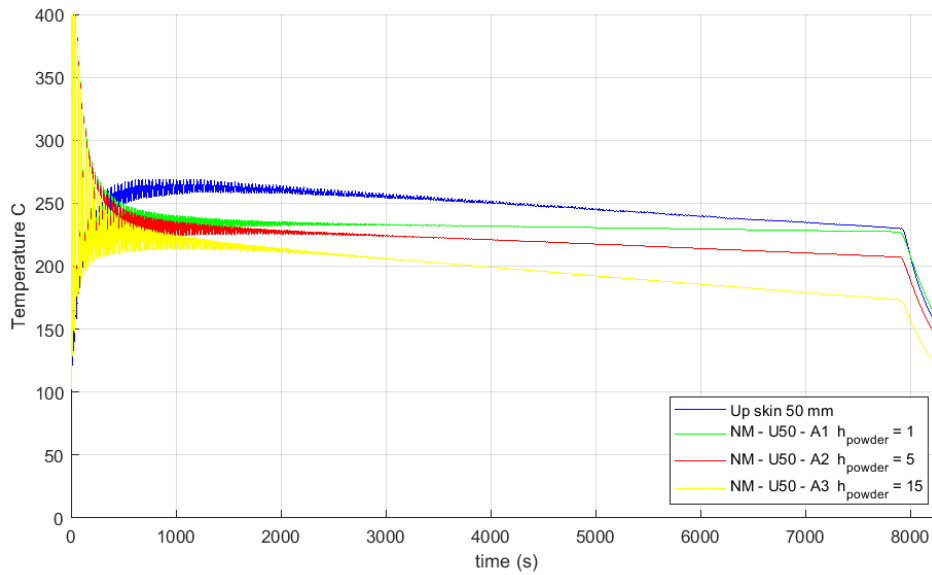


Figure 4.11: Temperature profile comparison of study A, between the experimental temperature Upskin (Blue) and the simulated temperatures.

Figure 4.10 and Figure 4.11 show the combination of results from parametric study A. It is possible to verify that the h_{powder} clearly affects the slope behavior. On A1, where the heat extraction through convection is the smallest, it is possible to see a quasi-state of temperature stability. This would not fit the experimental results (Blue) since it is expected to have a slight temperature

decay over time. Nevertheless, study A2 shares the same slope behavior as the experimental results. Study A3 has a steeper slope due to greater heat extraction through the geometry walls to the powder bed emulsion. Therefore, the powder convection, h_{powder} , has a clear impact on the slope behavior, which is a great tool to help calibrate the model. However, to find the best h_{powder} , a method of trial-and-error was taken which can slow down the calibration process.

An interesting study that could be further made is the implication and the repercussion of changing the T_{sink} . It would be expected that a high sink temperature would lead to a lower power extraction so that the slopes would not have the same steepness. On the other hand, the convection layer could heat the piece instead of cooling it down. If, for instance, the T_{sink} is greater than the manufacturing piece's average temperature, it would be possible to see the effect.

4.2.4 Change of bottom temperature - B

The second parameter tested is the baseplate temperature, T_{bottom} . In the following table, it is possible to see the chosen values of T_{bottom} while maintaining the rest of the parameters.

Table 4.2: Parametric study B, chosen parameters of T_{bottom}

Name	T_{bottom} [°C]
B1	50
B2	75
B3	100

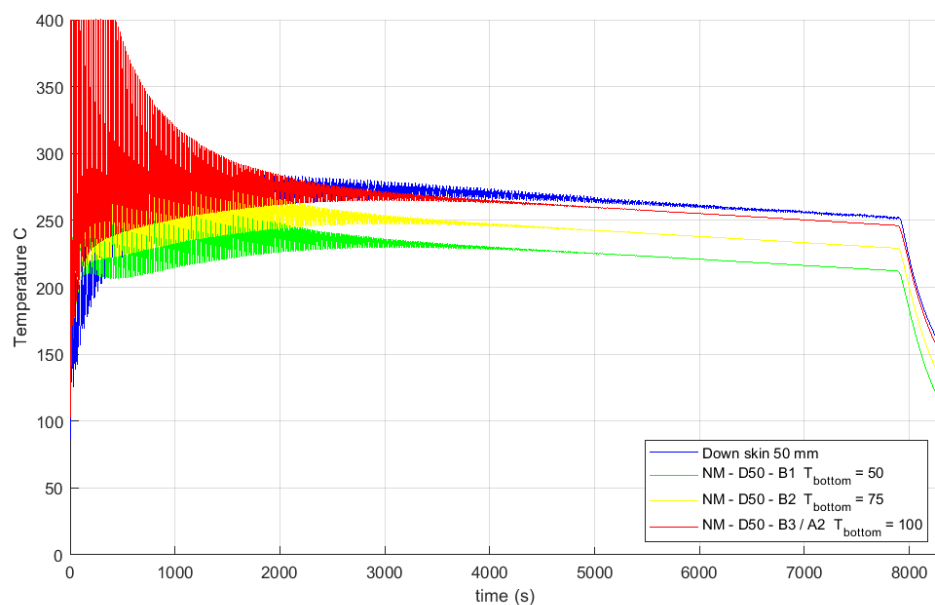


Figure 4.12: Temperature profile comparison of study B, between the experimental temperature Downskin (Blue) and the simulated temperatures.

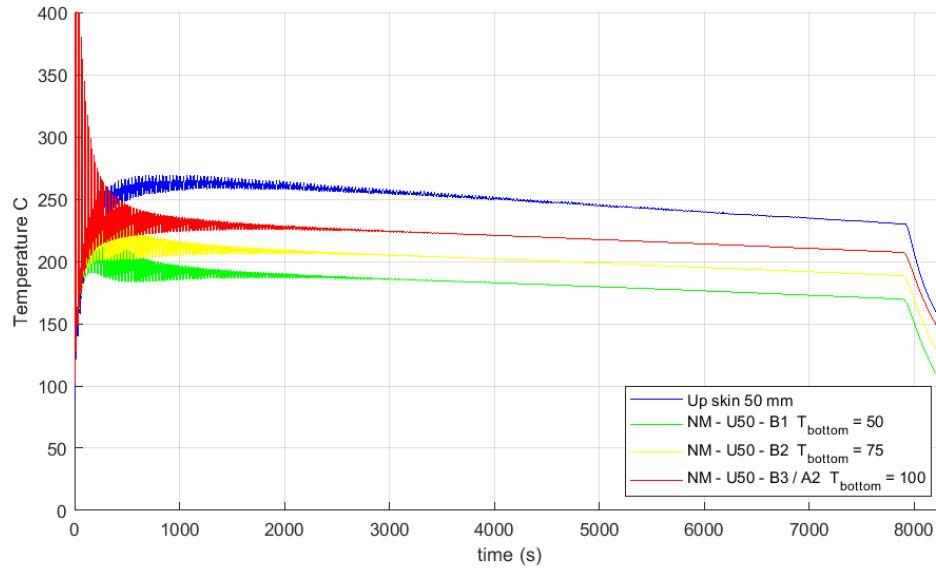


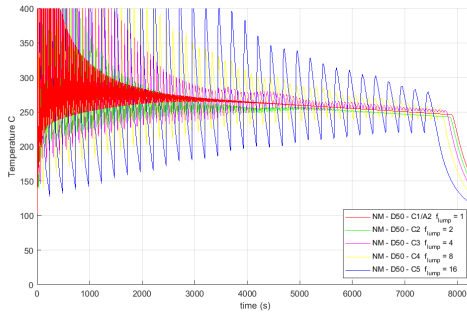
Figure 4.13: Temperature profile comparison of study A, between the experimental temperature Upskin (Blue) and the simulated temperatures.

Figure 4.12 and Figure 4.13 show the combination of results from parametric study B. Changing the bottom temperature T_{bottom} , has an apparent effect on shifting the average temperature. A lower bottom temperature brings the temperature profile lower, but it does not visually impact the steepness of the temperature profile. On B3/A2, it was used at the highest temperature possible. Nevertheless, it would be possible to bring the simulated validation to a more excellent match if the $T_{bottom} > 100$ °C. However, this value would have been unreal compared to the actual experiment, where the imposed temperature was 100 °C.

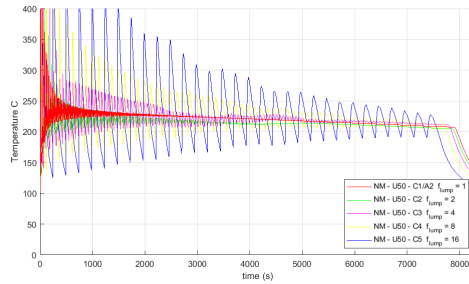
With study B, it is possible to understand the role of the imposed temperatures on the baseplate during AM process. Looking at the final cooldown of each figure, B1 presents the highest cooling rate. This will have a considerable impact on the final part quality. The temperature gradient mechanism is responsible for generating residual stresses and giving special characteristics to the microstructure. Therefore, this numerical modeling allows us to understand the behavior of a selected temperature on the baseplate and, qualitatively, the deformation aptitude. In other words, if we know that final deformation at $T_{bottom} = 100$ °C, we know that any value chosen under it will have a higher deformation value.

4.2.5 Change of layers in the lump - C

In study C, instead of understanding the physical behavior by changing a parameter, now, it is a simulation parameter that suffers the change, in this case, the number of real layers into a modeling layer, having the name of f_{lump} . On this study, it no longer makes sense to compare with the experimental result, and our reference becomes the validated simulation (A2). The Table 3.5 shows the values chosen for this study:



(a) Downskin data probe



(b) Upskin data probe

Figure 4.14: Temperature profile comparison of study C, between the validated simulation (C1/A2 Red) and the different f_{lump} simulations.

The previous Figures 4.14 represent too much information, making it difficult to interpret. Thus, it was chosen the minimum, intermediate, and maximum f_{lump} studied, C1, C3, and C5, respectively, and after presented in Figure 4.15 and Figure 4.16. Study C1 has been enhanced in red to identify better the validation behavior concerning the f_{lump} factor.

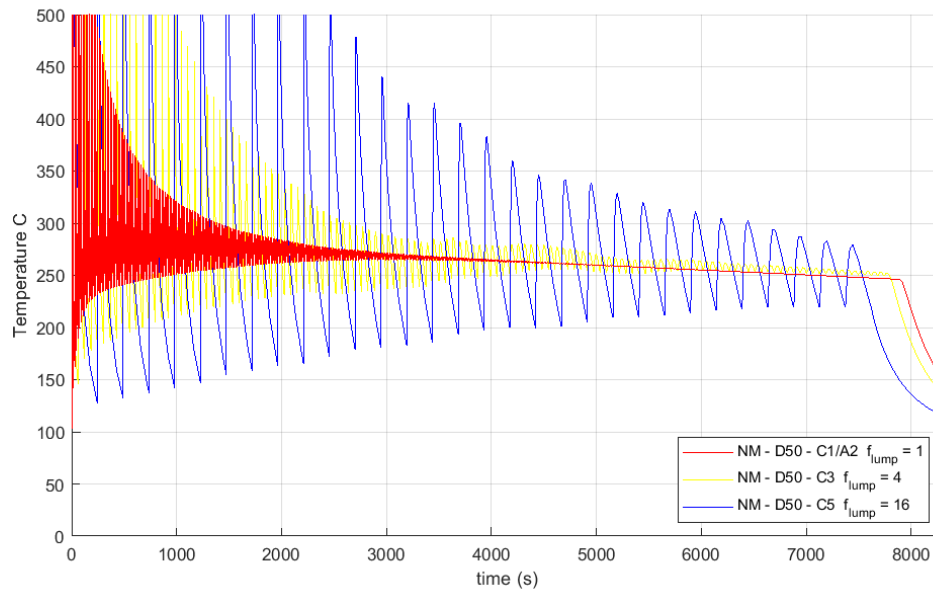


Figure 4.15: Temperature profile comparison of study C, between the validated simulation (D50 - C1/A2 Red) and the Downskin temperature of C3 and C5 simulations.

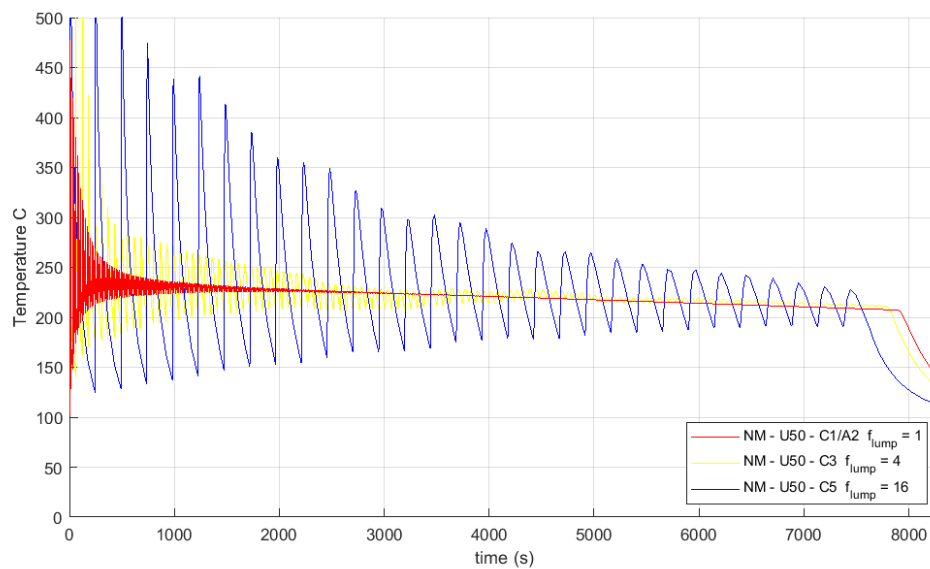


Figure 4.16: Temperature profile comparison of study C, between the validated simulation (U50 - C1/A2 Red) and the Upskin temperature of C3 and C5 simulations.

Visually, it is possible to observe that the general trend is kept even when the f_{lump} is changed. As the number of lumping layers increases, the temperature fluctuation for each layer increases. This is due to prolonged step time for high lumping numbers. The model's purpose and desired

precision determine the extent of lumping. The temperature data for lumping indicate that a greater number of lumped layers causes more significant oscillations. Despite the high value of lumping, the overall trend is nevertheless captured. Therefore, layer aggregation is a possible choice when the primary objective is to determine the overall temperature. However, history-dependent outcomes, such as microstructure evolution, cannot be predicted when the lumping technique is utilized because the local thermal history is not captured [48, 38].

To verify the correct agreement of average temperatures between studies, the Savitzky-Golay method was applied with the same polynomial order of 4. The results are shown in Figure 4.17 and Figure 4.18.

Nevertheless, the oscillation felt by lumping a higher number of layers could be increased its frequency and lower the peak temperature if we had used the "Multi-Shot Super-Layer" where for a $f_{lump} = N$, there would be N heating periods and N coolings. In contrast, on FH, for a $f_{lump} = N$, there is only one cycle for each lumped layer deposited. However, this would have a higher computational cost.

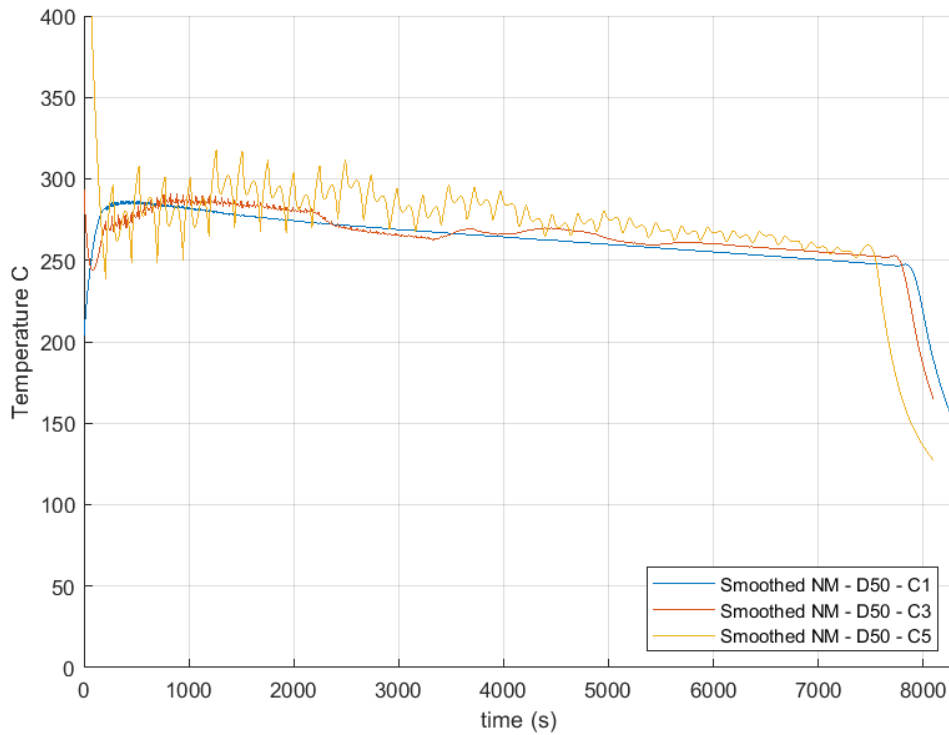


Figure 4.17: Smoothed temperature profile comparison of study C, between the validated simulation (D50 - C1/A2 Red) and the Downskin temperature of C3 and C5 simulations.

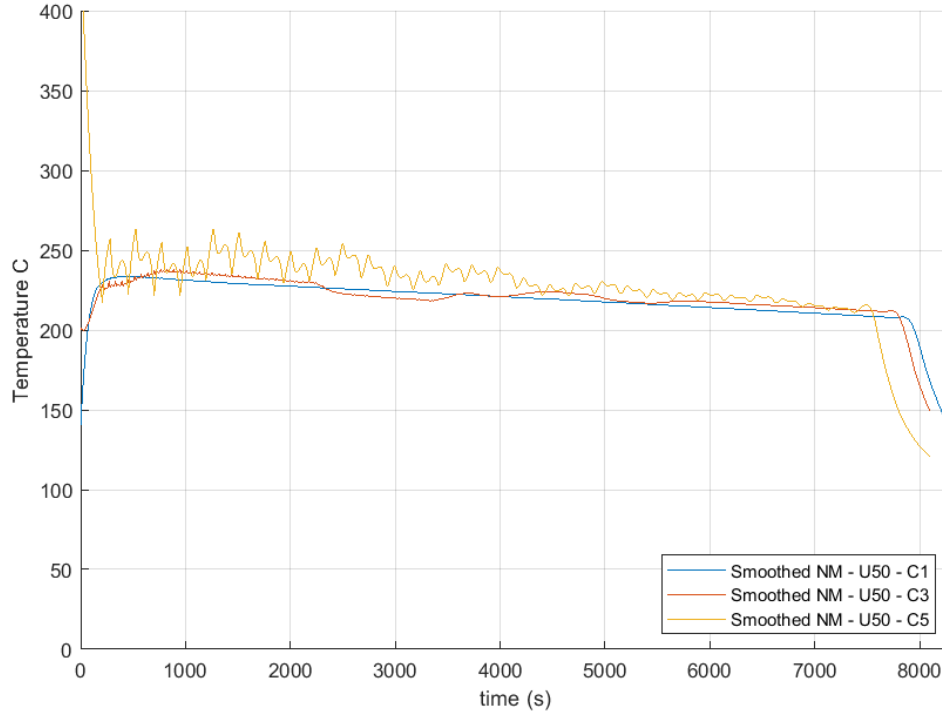


Figure 4.18: Smoothed temperature profile comparison of study C, between the validated simulation (U50 - C1/A2 Red) and the Upskin temperature of C3 and C5 simulations.

This method shows us the good agreement of all the studies to keep the general temperature trend, especially between C1 and C3. However, one problem arose when evaluating the Max temperature felt in each of the studies. The table 4.3 help us finding it out.

Table 4.3: Max temperature found during study C

Name	f_{lump}	Max Temperature [°C]
C1	1	1009
C2	2	1515
C3	4	2088
C4	8	3190
C5	16	4161

Knowing that Ti-6Al-4V titanium alloy has a melting temperature around $T_{melting} = 1660$ °C, it is possible to observe that studies C1 and C2 do not enter the melting phase. In other words, the highest temperature achieved on the validated model does not surpass the $T_{melting}$ point. This mistake was due to the fact that, in order to perform a faster validation process, it was chosen $f_{lump} = 4$, which can be seen on table 4.3, C3 respects the condition of melting phase. Study C1 and C2, with a contact time of $\Delta t_{cont} = 5 \times 10^{-2}$ s are in a gradual heating regime, which could not be

used to feed a weakly-coupled thermomechanical simulation since without achieving the $T_{melting}$ point, there will not be a correct physical representation of the problem where there is a melting pool, where different periods of solidification occur creating contractions within the component. This effect cannot be captured at temperatures below $T_{melting}$. Nevertheless, even without an FH approach, study C1 and C2 show the same behavior as the rest of the C simulations where they actually enter the melting phase.

After finding this particularity in our simulations, a quick simulation (less total height) was performed with only the contact time modified. Therefore, for a simulation with a $\Delta t_{cont} = 1 \times 10^{-4}$ s highest temperature was 4908 °C which enters already the melting phase zone.

Another goal of this study is to understand if sacrificing the local thermal history would bring advantages to simulation speed. Hence, Table 4.4 shows the different wallclock times of the simulations, where all the gray rows correspond to the validated simulation.

Table 4.4: Wallclock time of the studied simulations

Name	Wallclock time		
	Seconds	Hours	Days
A1	$3,55 \times 10^5$	98,61	4,1
A2	$4,24 \times 10^5$	117,78	4,9
A3	$4,15 \times 10^5$	115,28	4,8
B1	$3,56 \times 10^5$	98,89	4,1
B2	$4,19 \times 10^5$	116,78	4,8
B3	$4,24 \times 10^5$	117,78	4,9
C1	$4,24 \times 10^5$	117,78	4,9
C2	$2,11 \times 10^5$	58,61	2,4
C3	$1,30 \times 10^5$	36,11	1,5
C4	$1,29 \times 10^5$	35,83	1,5
C5	$6,74 \times 10^4$	18,72	0,8
E1	$4,13 \times 10^5$	114,72	4,8
E2	$3,58 \times 10^5$	99,44	4,1
E3	$4,24 \times 10^5$	117,78	4,9
E4	$4,01 \times 10^5$	111,39	4,6

It is possible to verify that all the simulations with a f_{lump} of one have an average of 4 days and a half (4,525 h). It is still a considerable number for such a simple geometry without complex overhangs or internal features. However, when observing the study C results, it is clear that increasing the f_{lump} significantly impacts the simulation time, whereas for a $f_{lump} = 16$, the simulation drops to less than one day. This could allow teams to optimize parameters and decide on the day after, thereby saving time and money. Another way to increase simulation speed would be having a coarser mesh or adding the minimal properties points into the simulation because fewer interpolation functions would be needed.

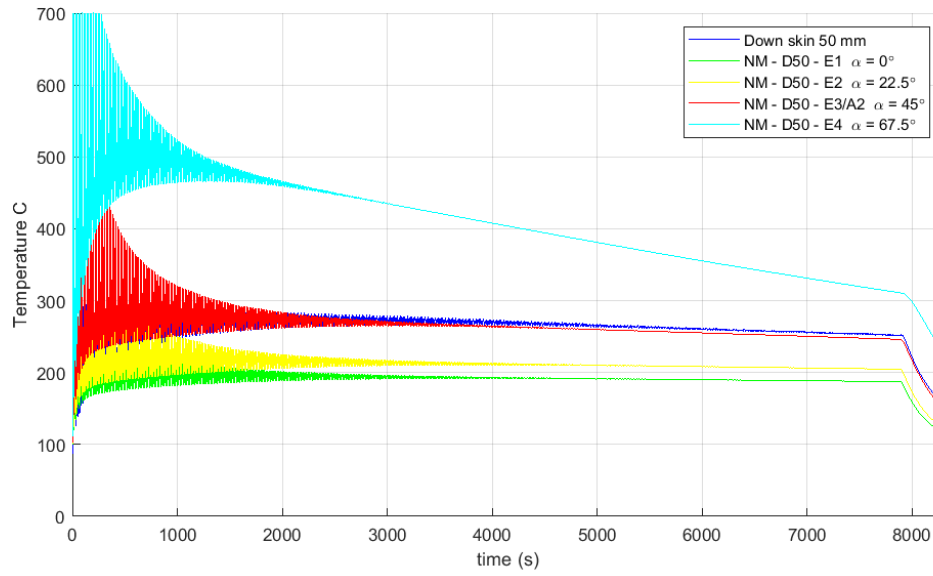


Figure 4.19: Downskin temperature profile comparison of study E, between the validated simulation (D50 - E1/A2 Red), the different overhang angles.

4.2.6 Change of angle in the geometry - E

In study E, the parameter changed is α . This angle is measured from the Z axis, as shown in Figure 3.25. In the Table 3.6, it is possible to see the chosen values of α while maintaining all the parameters as the validated simulation.

A temperature build-up will be expected on the down-facing or overhanging surface. This problem usually is fixed by adapting the input power or adding support structures. However, this increases the processing time and adds material that will have to be removed in post-processing, increasing the part's final cost. Figure 4.19 and Figure 4.20 shows the results obtained during study E. While observing these graphs, it is important to notice that the temperature axis changes scale from [0 - 400] °C to [0 - 700] °C.

As expected, when the angle α is zero, There is no difference between Up and Down Surface results.

The most fascinating result from the analysis is that the average temperature change does not have a linear effect. The E1 and E2 have the same average on the Up surface, Figure 4.20 and quite similar on the Down Surface. But the steeper the geometry inclination, the greater the thermal accumulation effect.

The E4 does not present the same horizontal behavior as the rest. This can mean that the result started not make physical meaning, which can be used as a pre-eliminatory study of the feasibility of an overhang. In other words, if the behavior of the temperature of a simulated object does not present a slope lower than a certain amount, it is necessary the implementation of support structures in order to allow a healthy heat transfer.

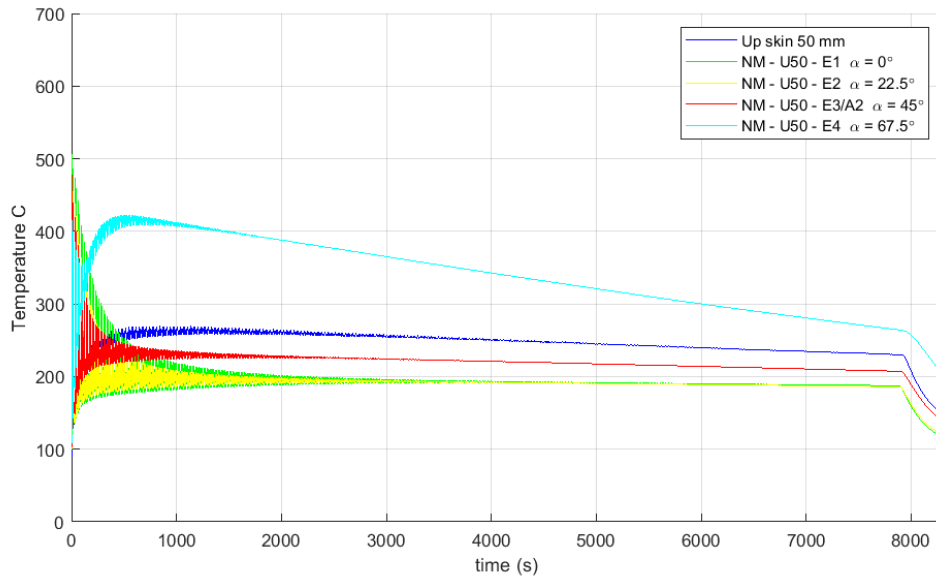


Figure 4.20: Upskin temperature profile comparison of study E, between the validated simulation (U50 - E1/A2 Red), the different overhang angles.

In order to execute a fair evaluation of these charts, the temperature was chosen at 4000 seconds from the beginning of the scanning. Therefore, tables 4.5 and 4.6 show the changing percentage from each 22,5° increment of α at 4000 seconds after the beginning of the manufacturing process.

Table 4.5: Temperatures at 4000 s in study E - Downskin surface

Name	α [°]	Temperature [°C]	Difference %
E1	0	193,59	
E2	22.5	211,79	9,40
E3	45	264,97	25,11
E4	67.5	407,76	53,89

Table 4.6: Temperatures at 4000 s in study E - Upskin surface

Name	α [°]	Temperature [°C]	Difference %
E1	0	193,59	
E2	22.5	192,13	0,75
E3	45	221,11	15,08
E4	67.5	342,65	54,97

The temperature of E1 and E2 of the Upskin surface has merely changed 0.75%, but soon after, it starts to behave similarly to the Downskin. Changing the overhang angle does more than changing how heat accumulates. It also changes the surface area in contact with the powder bed. Hence, the greater the angle, the more surface area is exposed to convection. The table 4.7 compares the different CAD models and shows the area that the Surface Downskin has in contact with the powder bed. The vast surface area can explain the E4 effect of rapidly decreasing the temperature in contact.

Table 4.7: Surface area of the study E geometries

Name	α [°]	Surface area [mm ²]	Area difference [%]
E1	0	2000	
E2	22,5	2165	8,24
E3	45	2828	30,66
E4	67,5	5226	84,78

Chapter 5

Conclusions and Future Work

The fundamental purpose of this dissertation was to develop a part-scale thermal model to predict temperatures generated during L-PBF. It was possible to explore the commercial CAE software ABAQUS, its formulation of AM thermal problems, and its versatility with python scripts conducting parametric studies on some of its input variables. The Flash Heating model was successfully calibrated with experimental *in-situ* values.

Most of the actual modeling approaches are still far from the actual capabilities of the AM machines. Simulations are still limited to some extent in their geometry and complexity.

Research indicates that process parameters have a considerable effect on L-PBF component quality. Consequently, the developed thermal model could incorporate a Design of Experiment (DoE) research to collect important information on optimizing the process parameters and enhancing the quality of the final components. While an experimental DoE may incur additional expenditures for the organization, a numerical DoE conducted using simulations saves those costs. This project demonstrated that accurate models could be created to estimate the temperature development during the manufacturing process, from which most of the component's final attributes are obtained. This is an important achievement in this industry since it will ultimately result in fewer discarded parts owing to mechanical faults and lower expenses connected with AM procedures, particularly MAM.

The main conclusions that were reached are presented below:

- With the help of numerical modeling, it is possible to develop well-behaving models that represent physical experiments with some degree of confidence;
- By neglecting the meso-scale physics and implementing a layer-by-layer approach into a part-scale model. It is possible to gain MAM simulation speed with the inherent cost of losing the local thermal history;
- The mesh of a FEM system has a crucial impact on the final simulation quality, either physic-wise or computational-wise;

- With the part-scale thermal model, it is possible to capture the overheating effect and build-up temperature along the manufacturing process, which generate hotspots. These simulated spots could therefore be a suggestion of a possible region with keyhole porosity;
- In the parametric study, the powder convection coefficient had the most significant impact on the steepness of average temperature along the process. In contrast, the imposed temperature at the bottom of the baseplate has the power to shift the temperature profile, maintaining the general slope completely. The hotter the bottom temperature, the higher the average temperature was during the process. This will have a direct impact on the thermal gradient mechanism, hence, influencing a possible residual stress study;
- When the number of layer lumped increases, the simulation times decreases while maintaining the average temperature trend;
- By changing the overhang strongly impacts the thermal behavior along the part. Overhang, with a high inclination, behaves strangely in the thermal model, which can prove the need for structural supports for heat dissipation.

5.1 Further Work

In order to optimize the numerical model and improve the results obtained in the duration of this project, some suggestions are provided:

- It would be interesting to have more thermocouples in different parts of the component, such as baseplate or different heights of the pre-build, in order to calibrate the model better;
- Perform experiments with the same parameters but with different overhang angles as shown in study E, and extract in-situ measurements for further analyses;
- Compare the thermal model with other modeling techniques, like the Multi-Shot Super-Layer, and check potential differences in the computation times and the predicted temperatures;
- Compare the thermal model using different element birth and death elements, for example, quiet element method or hybrid quiet inactive method, and check potential differences from the inactive method used in this work;
- Reduce the dimensions of the output files from the thermal simulation and rewrite the information into a pixelized .png database. To achieve faster study between in-situ and simulation results;
- So far, only one set of process parameters has been validated and simulated. To show the reliability of the FH method from the process parameters, it would be nice to produce simulations from other energy densities and show the consistency of the results;

- After finding that study C1 and C2 behave in a gradual heating mode, it would be beneficial to perform a contact time sensibility analysis;
- Use this model to input the thermal response for a weakly-coupled thermomechanical model in order to capture the residual stresses;
- Study the normalized enthalpy of the AM through the numerical modeling;
- Turn the script into a non-geometry-dependent to automatically read each deposited layer's area.

Appendix A

No overhang geometry - *The first approach*

This appendix explores the initial research work performed, which had to be discontinued due to the lack of information regarding experimental data. However, it proved helpful to understand the guidelines better to develop a well-behaving model. With this in mind, the following appendix will be divided into two sections: Section A.1, which is an experimental setup introduction to the geometry without overhang; Section A.2, which delves into the problems found during the development of the first thermal model.

A.1 Experimental setup

An experimental campaign is conducted to calibrate a thermal analysis FE framework at the Monash Centre for Additive Manufacturing (MCAM) in Melbourne, Australia [42].

The EOSINT M280 from Electro Optical Systems (EOS) GmbH is the printing system utilized for the experiments. It employs a Yb-fiber laser with variable beam width and up to 400 W of power. To avoid oxidation of the component, the printing procedure is performed in a $250 \times 250 \times 325 \text{ mm}^3$ room with a controlled argon environment. The flow of argon is kept laminar. Figure A.1 depicts the part geometry, which consists of two specimens produced simultaneously: a thin wall measuring $5 \times 80 \times 50 \text{ mm}^3$ and a thicker wall measuring $40 \times 80 \times 50 \text{ mm}^3$. The distance between the two walls is 40 mm. The dimensions of the construction plate are $252 \times 252 \times 45 \text{ mm}^3$ [42].

The thermocouples used to monitor temperature are placed into distinct holes on each of the two specimens. To do this, the printing process must be interrupted after an initial deposition of 20.24 mm, and the powder bed must be removed. This particular step, which is also followed in this thesis, can be better seen in Figures A.4. Each sample has four thermocouples, with the first three separated by 5 mm in the vertical direction and the fourth displaced 10 mm horizontally from the top thermocouple. To simplify further explanations, the rest of the appendix is focused on the thick wall specimen. Therefore, the thermocouple placement is shown in Figure A.2.

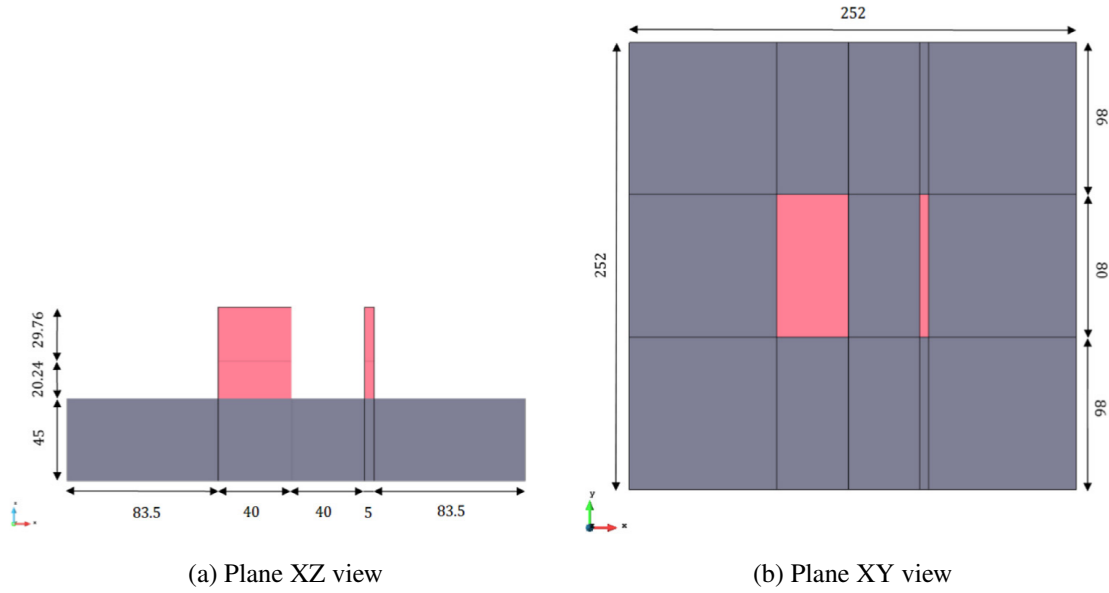


Figure A.1: Base plate and printed geometries [42].

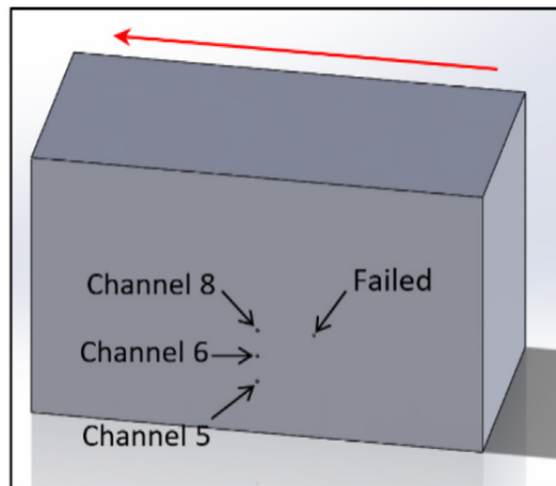


Figure A.2: Location of thermocouple channels at the thick wall [42].

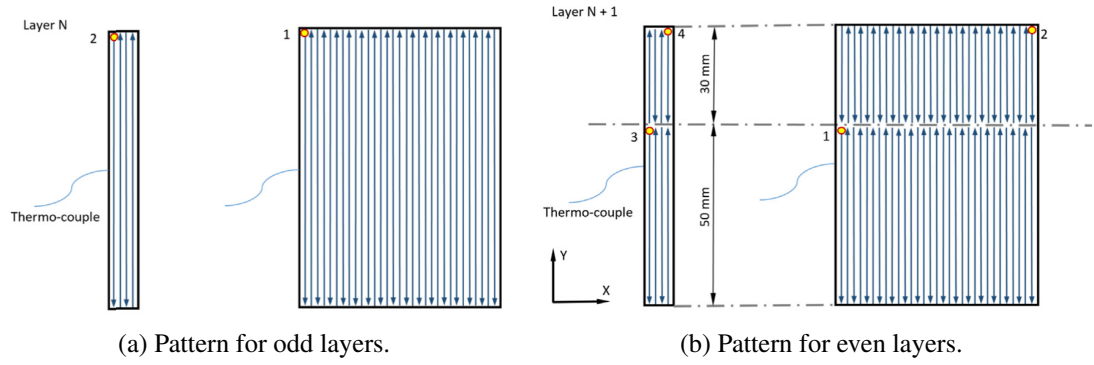


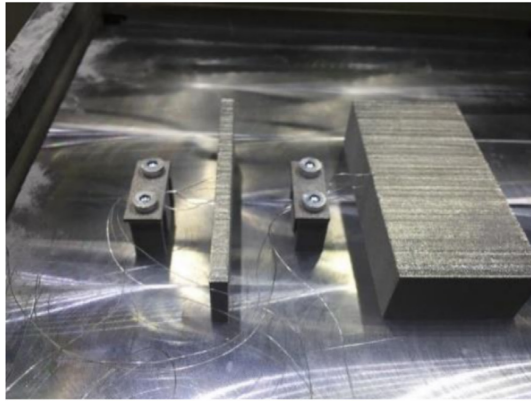
Figure A.3: Scanning pattern used in the printing process. Starting points are indicated with circles [42].

K-type thermocouples and a Graphtec GL-900 8 high-speed data-logger are adopted for data collection. Temperature data could only be collected from the channels placed vertically, as the channel placed horizontally was damaged during setup. The sampling rate of the data logger is one millisecond per second, while the time constant of the thermocouples is seven milliseconds per second [42].

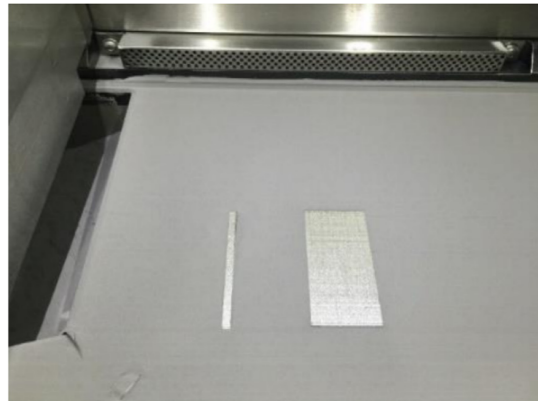
The printing method uses the same process settings as the experiment described in Section 3.1. The layer thickness is adjusted to $30\ \mu\text{m}$. Therefore 992 layers are deposited in approximately 33,500 s (nearly 9 hours) to construct the samples.

A unidirectional scanning method is implemented along the longitudinal axis of both samples. Figure A.3 illustrates the scanning sequence employed throughout the printing process. The scanning route alternates between layers that are odd and even. Note that the number of hatches illustrated does not match the real number of hatches, which is significantly wider based on the power beam size. The printed samples are made of the same Ti-6Al-4V Titanium alloy used in Section 3.1.

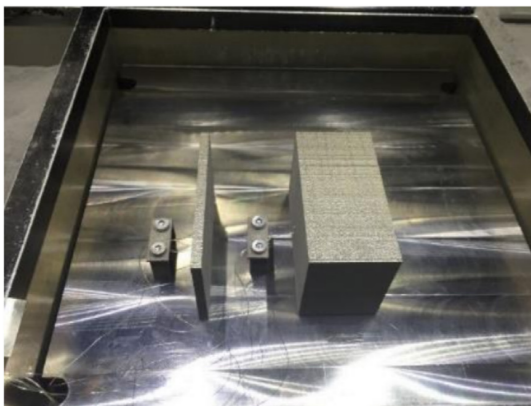
The results obtained from the *in-situ* monitoring can be seen in Figure A.5. As previously mentioned, the fourth channel is ignored due to troubles during the experiment.



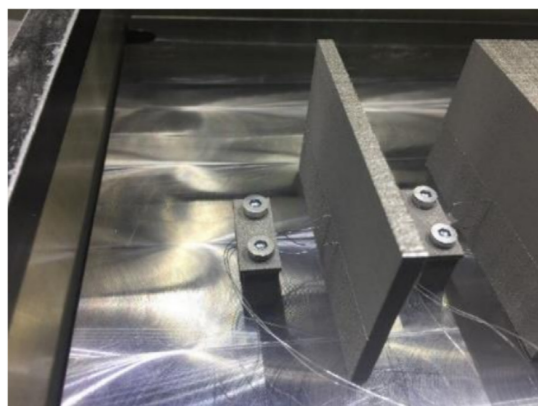
(a) The printing job is interrupted, the powder bed is removed, and the thermocouples are inserted.



(b) The powder bed was replaced, and the printing job was resumed.



(c) After finishing the printing job, the powder bed is removed from the building platform.



(d) A closer picture shows the position of the thermocouples throughout the printing process

Figure A.4: Steps done in order to capture the *in-situ* temperatures [42].

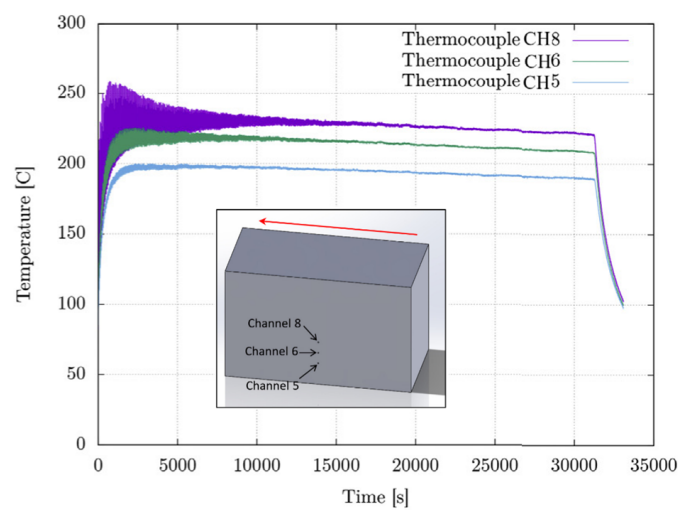


Figure A.5: Experimental data gathered on the thick wall [42].

A.2 First thermal model

The modeling strategy uses the Flash Heating method, which is explained during the thesis. The thermal properties and process parameters are the same as Chapter 3.

Finite elements

The thermal analyses use eight-node linear diffusive heat transfer brick elements (DC3D8). The model's meshing was not uniform throughout the component. The fine mesh was used for the layers to be printed, the medium mesh was used for the originally created thermocouple portion, and the coarse mesh was used for the build plate. Figure A.6 displays one example of the mesh used in the FEM simulations.

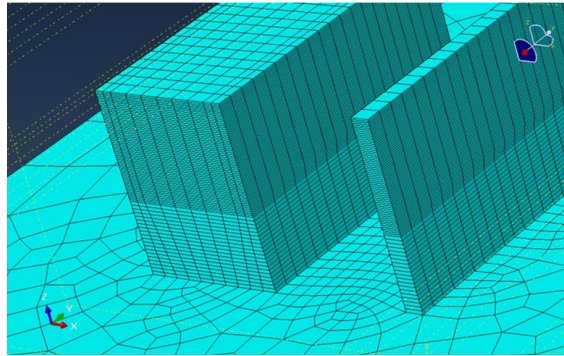


Figure A.6: Detail from meshed geometry example.

The boundaries condition, in this case, were radiation on the top surface and convection on the baseplate bottom with a $T_{sink} = 25\text{ °C}$. The convection coefficient, h_{bottom} , is one of the tools to calibrate the model. This approach differs from the one used during the thesis' work.

Lack of diffusion

The simulation values compared are nodal temperature values (NT11). Throughout the validation attempts, the results presented are from the thermocouple at CH8 for ease of visualization. The temperature profiles are similar, and the temperature data offsets from experimental results are constant for each thermocouple/node. Figure A.7, shows one of the first validation attempts.

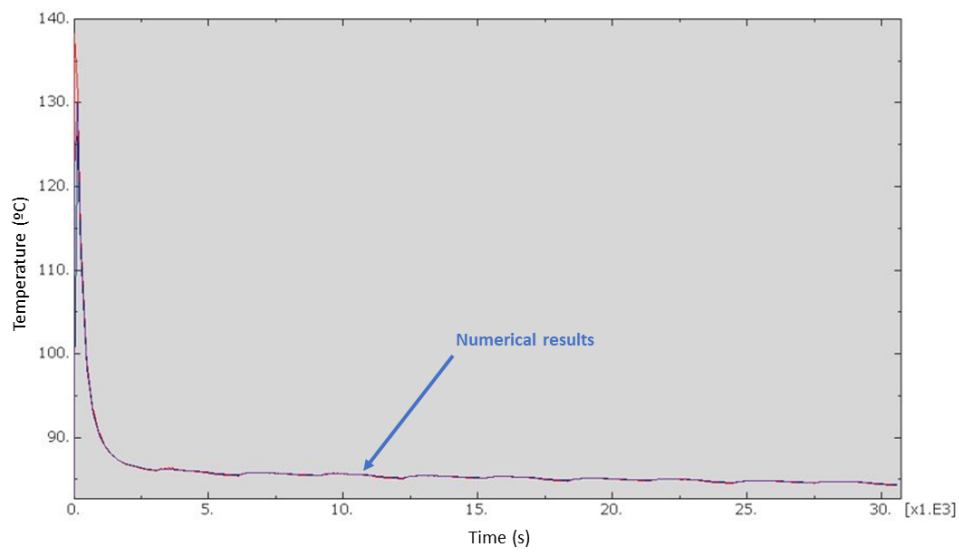


Figure A.7: Simulated temperature profile

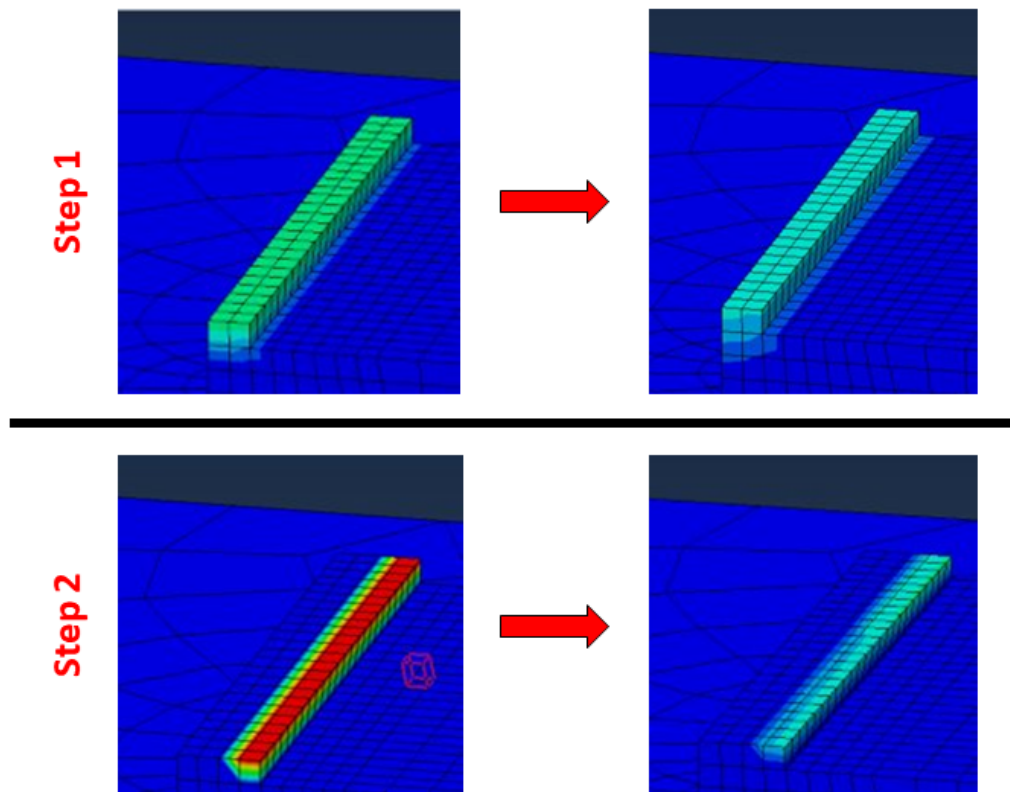


Figure A.8: Lack of diffusion after the Step 1.

At the beginning of this validation process, we faced an interesting simulation behavior when activating a new cell and, at the same step, activating the heat body flux. The temperature profile

was acting in a completely different way as expected. Nevertheless, if looking to Figure A.8, it is possible to verify that only the first element that was not disabled initially could adequately conduct the heat received. Moreover, by increasing the f_{lump} , the worst this effect actuates.

However, as later found in ABAQUS's manual, to protect the simulation convergency, when using the ABAQUS feature "model change", the material properties are ramped up, starting from zero. This will provoke the effect in Figure A.8. The small time contact, Δt_{cont} , will apply much energy to a body with low conductivity, and only later in the step time it progressively conducts the heat received.

Therefore, the solution is splitting the step into Activation and Depositioning steps. The activation step has a small value, allowing ABAQUS to activate the elements needed and ramp up their properties before the body heat flux is activated. Moreover, soon after, the Depositioning step will apply the thermal load during the time contact, Δt_{cont} . After implementing this new strategy, we finally got an interesting trend, although not calibrated, as seen in Figure A.9.

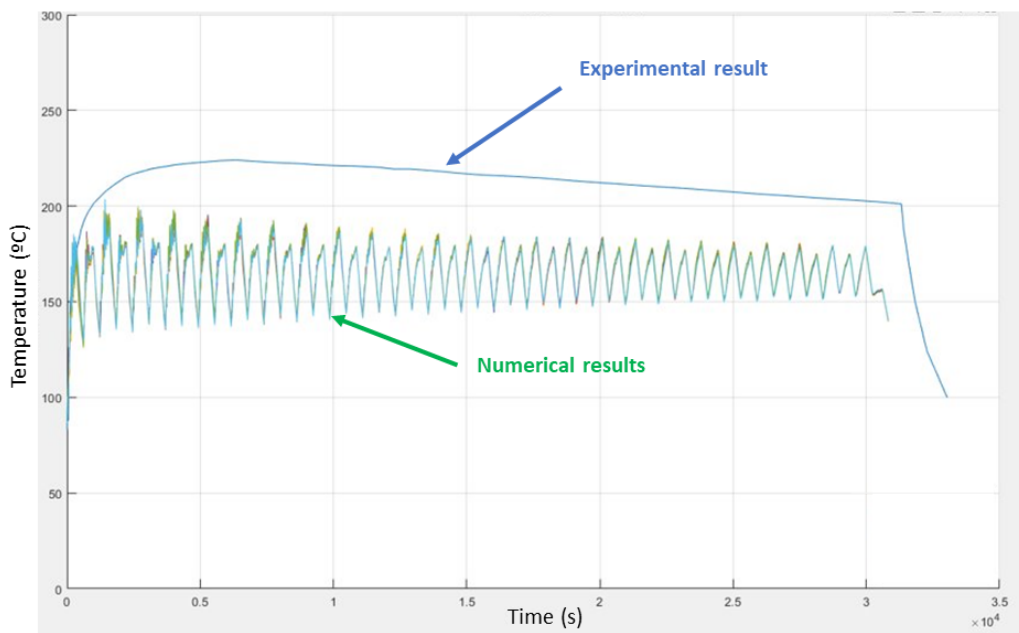


Figure A.9: Simulation temperature profile after implementing the Activation Step.

Heat sink problems and overshoot

Another effect found during the development of the thermal model was when there is a lack of refinement into the XY plane, it generates heat sink, as shown in Figure A.10. Heat sinks could capture the heat, and the model would incorrectly predict the temperatures in the thermocouple region. This happened when there was a coarse mesh, and the interpolation error had a more significant impact.

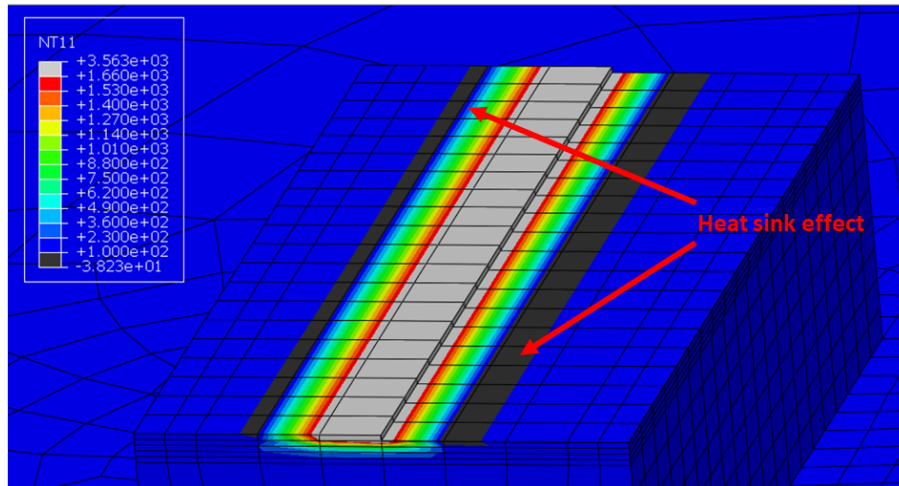


Figure A.10: Heat sink effect. Negative temperatures are caused by overshooting.

Furthermore, the black regions had negative temperatures, which should be physically impossible with the input conditions. However, this occurs when the solver overshoots to converge in an exaggerated coarse mesh.

Further discussion

After these issues were solved, the results were still not satisfactory. Figure A.11 shows a study where three different values of h_{bottom} were applied, 15, 20 and 25 ($Wm^{-2}K^{-1}$) compared with the experimental value and a constant temperature of 100 °C.

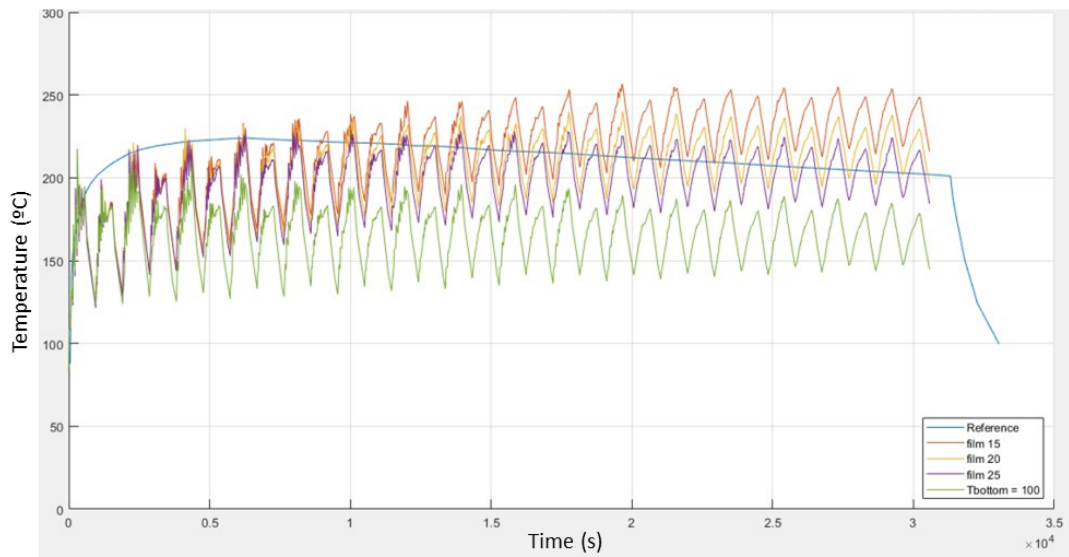


Figure A.11: Simulation temperature profile with different bottom conditions (experimental result marked as "Reference").

It is possible to observe that the smaller the h_{bottom} , the greater the overheat effect. However, it did not have the same trend as the experimental data. The condition that better match with the experiment was a $h_{bottom} = 25 \text{ (Wm}^{-2}\text{K}^{-1}\text{)}$, $T_{sink} = 25 \text{ }^{\circ}\text{C}$ with a $\Delta t_{cont} = 5 \times 10^{-2}$.

However, there was not all the information needed to continue this calibration. Therefore, attempts were made to communicate with fellow researchers who wrote the research paper. After receiving help from Dr. Zhuoer Chen, who kindly helped with information about a similar experiment that tries the same experimental approach as the one above-mentioned, and with his support, it was possible to start to develop the modeling of the new system. A system that is the one studied with more attention during this thesis' work.

Appendix B

Manuscript under preparation to be submitted to an international journal

This appendix intends to show the scientific article in preparation to be submitted. This article is a summary of the work performed during the thesis. Explanation of the Flash Heating method as well as the experimental work performed.

Thermal modeling of the Laser Powder Bed Fusion process: a numerical and experimental work

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SAGE

João Gomes¹, Mohamad Bayat² and Marco Parente¹

Abstract

Metal additive manufacturing (MAM) has experienced tremendous growth because of its enhanced production capabilities and the innovative design concepts it enables. Due to the multi-physics character of MAM, it is still difficult to predict temperatures and stresses during production, necessitating multiple experimental tests or numerical simulations to obtain the appropriate components. The work shown involves the development of a computationally efficient part-scale thermal model using an Flash Heating method to reliably predict temperatures generated during Laser Powder Bed Fusion (LPBF) of Ti-6Al-4V Titanium alloy. Subsequently, the model is calibrated through comparisons with thermocouples *in-situ* recordings extracted during manufacturing. Furthermore, after obtaining a well-behaving model, reliability tests on the thermal model are executed in order to understand the model's performance. The analyses go through boundary condition changes, the number of layers lumped, and the overhang effect on the temperature distribution during the manufacturing process. The studies demonstrate the impact of heat accumulation on the overhangs and prove that lumping layers significantly impact computational performance. From one layer lumped to sixteen layers, we go from 117 hours to 18 hours of simulation. Lastly, a MATLAB code was created to extract and process simulation data for later analysis with *in-situ* measurements taken during the experimental process with photo-sensors, where it was possible to observe cold and hotspots.

Keywords

Metal Additive Manufacturing, Numerical Modeling, Flash Heating Method, Thermal Simulations

Introduction

Since its original creation, Metallic Additive Manufacturing has experienced a significant increase in popularity. The ability to produce parts with low geometrical limitations is unmatched, especially with numerical methods such as topology optimization. These technologies can considerably reduce the component's bulk dimension while keeping its structural integrity, as being able of developing exceedingly complicated shapes that no other manufacturing procedure could easily reproduce. Meanwhile, in AM, novel materials like Titanium alloys with their high tensile strength-to-weight ratio are frequently employed (1; 2; 3).

Although AM technologies have other advantages beyond geometrical flexibility, such as reduced design cycle times, but it is still challenging to predict the manufacturing results since the process is both highly transient and possesses localized physics (micro and meso scale) (4; 5). This typical AM thermal behavior introduces defects that must be accounted for: excessive surface roughness, dimensional imprecision due to the heat cycles during layer deposition, microstructural defects due to the part's interaction with the surrounding atmosphere and rapid cooling, and residual stresses (6).

Under two distinct situations of inadequate and excessive heat input, L-PBF may develop voids or internal porosities. In particular, the former state results of an absence of fusion while the latter is in keyhole-induced holes (2; 7). *Ex-situ* and *in-situ* examinations are two methods for finding various sorts of porosities. The *ex-situ* research would provide

inadequate information regarding how pores are created and hence would not identify the processes responsible for developing these spaces. Moreover, *in-situ* monitoring devices are sometimes prohibitively costly and might pose health risks to operators; hence, they cannot be utilized regularly to observe these physical events (7). In addition, online monitoring must have preparations and calibrations beforehand, significantly increasing the entire analysis time. Moreover, the coexistence of numerous interactive phenomena, such as recoil pressure, the Marangoni effect, evaporation, laser reflection, etc., all occurring within microseconds, makes it exceedingly difficult to study the keyhole and its subsequent pore formation mechanism through experimentation alone (7).

Therefore, this work's motivation is to create a well-behaving model that can capture most of the thermal behavior of an LPBF process by using experimental data to calibrate and afterwards test its reliability. When validated with experimental results, it will allow the ability to test different parameters without the cost of producing a piece based on a trial-and-error method to detect defect formation.

¹Faculty of Engineering, University of Porto, 4200-465 Porto, PT

²Department of Mechanical Engineering, Technical University of Denmark, building 425, Lyngby, DK

Corresponding author:

M. Parente Faculty of Engineering, University of Porto, 4200-465 Porto, PT.

Email: m.parente@up.pt

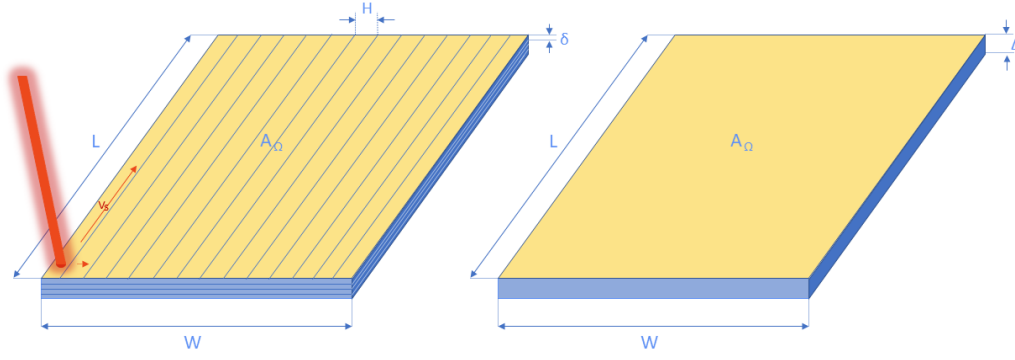


Figure 1. (Left) Actual layer (with thickness δ) and (right) meta-layer (with thickness Δ).

Numerical modeling with Flash Heating method

The objective is to develop a thermal model that can represent an LPBF process without entering the mesoscale with its inherently excessive computational time due to the phenomena' complexity. All of this while maintaining physical reliability (1; 7; 4).

Flash Heating (FH) is a method based on lumping layers that reduces computational time and resources in part-scale simulations with the inherent cost of losing local thermal accuracy. For a conventional gradual heating layer-by-layer model, the loading time of the volumetric heat source is equivalent to that of the actual experimental layer build time. In contrast, for FH, it is a fraction of the actual. This will allow reaching temperatures above the $T_{melting}$ to originate residual stresses. However, since this model ignores the real melt pool, laser heat sources, and scanning approach, its application is limited.

When constructing an FH model, it is essential to comply with both time and energy consistency. The concept of time consistency relates to the activation times of the layers. At the start of the simulation, all patches are disabled unless the first layer with its respective heating effect. Then, successive layers should be deposited with a progressive activation corresponding to the experimental deposition timings. To have a numerical model that respects the physics underlying melting time, the quantity of heat delivered to the layer in simulations must match the amount of energy supplied to the powder during the scanning. These two requirements are essential for ensuring the validity and reliability of the simulation since they must demonstrate the correspondence between the numerical model and the experiment.

Lastly, to ensure the accuracy of the FH approach, Δt_{cont} must be much shorter than the layer deposition time of the considered meta-layer, Δt . The deposition should be heated for a brief time to ensure that the melt phase is achieved and to allow heat energy to conduct throughout the remainder of the geometry. If $\Delta t_{cont} \rightarrow \Delta t$, the maximum temperature of the deposited material will decline until there is no pool of liquid melt. The latter, known as Gradual Heating (GH).

Governing equations

In the analysis for the current project, the melt pool and related phenomena are not considered. Therefore conduction is the predominant mechanism of heat transfer inside the component. The method is followed in greater detail in M.Bayat et al. (6) study.

Ignoring the material laser interaction with the powder and using an equal volumetric heat source for a predetermined contact time. The input energy of the layer can be computed using,

$$U_i = \eta \cdot P \cdot t_f \quad (1)$$

Where U_i is the input energy (J), η is the power absorptivity (-), P is the laser power input (W), and t_f is the time required to scan one layer (s).

But t_f is given by,

$$t_f = \frac{A_\Omega}{H \cdot v_{laser}} \quad (2)$$

Where A_Ω is the top surface area of the layer (m^2), v_{laser} is the laser scan speed ($m \cdot s^{-1}$) and H is the hatch distance (m). The top surface area is also given by,

$$A_\Omega = W \cdot L \quad (3)$$

Where, W is the width of the part (m) and L is the length of the part (m), by substituting equation 3 in equation 2,

$$t_f = \frac{W \cdot L}{H \cdot v_{laser}} \quad (4)$$

Substituting equation 4 in equation 1,

$$U_{i,\delta} = \eta \cdot P \cdot \frac{W \cdot L}{H \cdot v_{laser}} \quad (5)$$

Figure 1 shows that for Flash Heating, the component with actual layer height δ (m) is combined with numerous layers to calculate meta layer height Δ (m). Consequently, the ratios of their layer input energies can be represented as follows:

$$U_{i,\Delta} = U_{i,\delta} \cdot \left(\frac{\Delta}{\delta} \right) \quad (6)$$

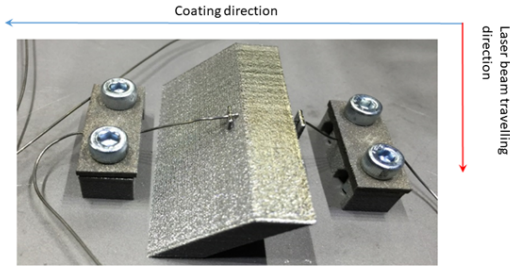


Figure 2. Closer look into the special experimental step for the thermocouples installation.

Where U_{Δ} is the input energy of the layer for the metalayer. To determine the volumetric heat source for the metalayer, divide equation 6 by the layer's volume and contact time, Δt_{cont} (s),

$$\dot{Q}_{\Delta}''' = \frac{U_{i,\Delta}}{\Delta t_{cont} \cdot (H * L * \Delta)} \quad (7)$$

Further substituting equation 6 and equation 5 in equation 7,

$$\dot{Q}_{\Delta}''' = \frac{\left(\eta \cdot P \cdot \left[\frac{W * L}{H \cdot v_{laser}} \right] \right) \cdot \left(\frac{\Delta}{\delta} \right)}{\Delta t_{cont} \cdot ([W * L] \cdot \Delta)} = \frac{\eta \cdot P}{H \cdot v_{laser} \cdot \Delta t_{cont} \cdot \delta} \quad (8)$$

This will be the primary equation to model the volumetric heat source for FH's meta layers.

Experimental campaign

It was decided to use a made experiment to start working on a validation model. We receive cooperation from Z.Chen et al. (8) with his experiment work at Monash Center for Additive Manufacturing (MCAM) in Melbourne, Australia.

The material chosen for the experiment was a gas atomized Ti-6Al-4V powder since it has received much attention due to its high strength-to-weight ratio (2). The powder used had a feedstock distribution of D10, D50, and D90 of 16 μm , 30 μm , and 50 μm (8; 9). At the beginning, a temperature of 100 $^{\circ}\text{C}$ was imposed on the substrate, and the EOS M280 chamber was pre-filled with Argon gas until the oxygen context was lower than 1000 ppm (8).

The specimen used was the 50 millimeters, built with the process parameters according to M.Chiumenti et al.(10). The laser was set to scan in a unidirectional pattern along the Y axis as it can be seen in Fig. 2, with the default contour scan setting deliberately deactivated.

Numerical results and discussion

All simulations were executed in the High-Performance Computing (HPC) cluster of DTU, with eight cores used for each run. The simulations were built in the FEM-based commercial software package ABAQUS / CAE 2018 using the FH method generated by Python scripts.

Validation and Calibration

The thermal model is successfully validated while using a contact time of $\Delta t_{cont} = 5 \times 10^{-2}$ s. This well-behaving

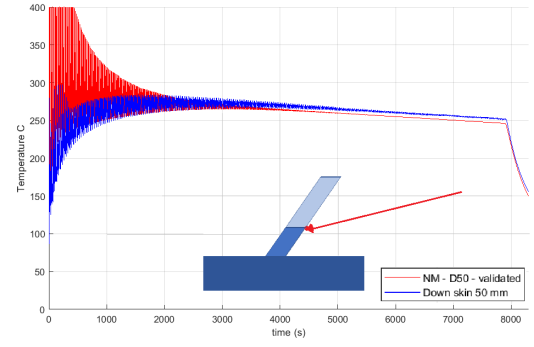


Figure 3. Temperature profile comparison between the experimental temperature Downskin (Blue) and the simulated temperature Down (D50 - Red).

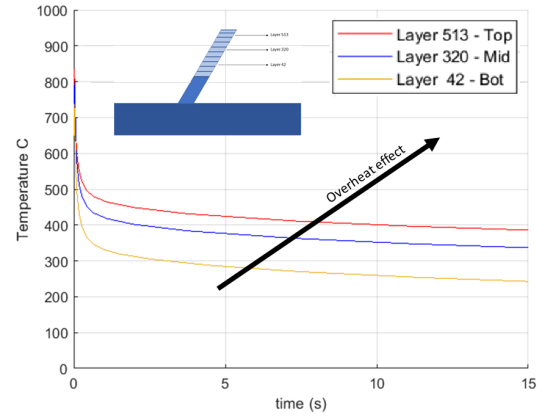


Figure 4. Temperature profile comparison of the first cooldown of different layers along the manufacturing process.

model was obtained for such geometry when the absorptivity is equal to $\eta = 0,45$. A powder convection of $h_{powder} = 5$ [$\text{Wm}^{-2}\text{K}^{-1}$] and sink temperature of $T_{sink} = 100$ $^{\circ}\text{C}$. The bottom boundary had a constant temperature of $T_{bottom} = 100$ $^{\circ}\text{C}$ while the radiation boundary of a new deposited layer had a emissivity of $\varepsilon = 0,4$ and a room temperature of $T_{amb} = 35$ $^{\circ}\text{C}$. The presented simulation results are always from the Downskin surface. The validation result is given in Figure 3.

The numerical validation underestimates the experiment temperatures. This can be due to ignoring the powder domain or from extracting too much heat from the piece, or even an interpolation problem, where some heat can disappear due to the overshoot of the temperature differences. For the validation results, the RMSE method was applied. The RMSE of the Down surface validation is 24,8 $^{\circ}\text{C}$. However, the simulation results show the same behavior as other research studies where the first layers have a significant thermal oscillation (10). This can considerably impact their evaluation; therefore, if we take out the first 1000 seconds of the simulation to better analyze, the RMSE value comes to 11,8 $^{\circ}\text{C}$ getting 52,5% closer to the reference value.

When analyzing Figure 4 different cooling rates are detected when increasing the distance from the baseplate. The higher the build, the greater the average temperature found. This proves the existence of overheating effect. The overheat effect is noticed when thermal energy input is not carried to the baseplate rapidly enough, resulting in localized overheating or heat buildup—overheating causes surface

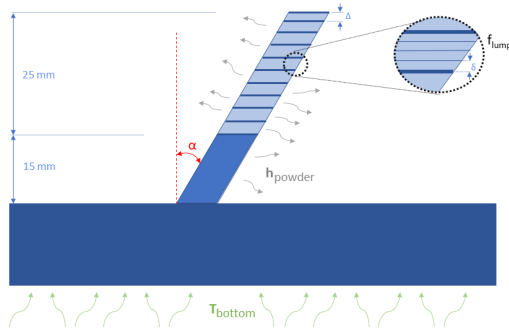


Figure 5. Schematic representation of the parameters studied.

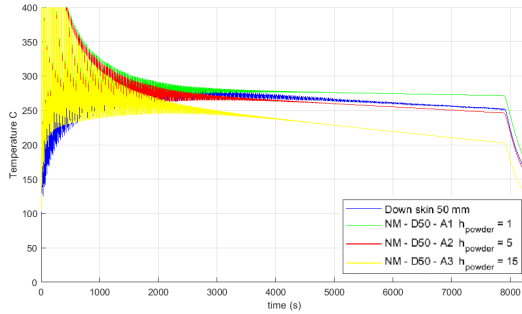


Figure 6. Temperature profile comparison of study A, between the experimental temperature Downskin (Blue) and the simulated temperatures.

flaws, such as balling and dross formation, that degrade the quality of produced components (11). In addition, local overheating can harm microstructural development, significantly affecting the final physical qualities and leading to build failure. Overheating also considerably adds to residual stresses that cause component deformation (12).

Parametric studies

After the numerical validation, an arrangement of tests is performed to study the usability of the numerical modeling and its reliability. Further tests are conducted:

- Convection coefficient of the powder, h_{powder} ;
- Bottom temperature, T_{bottom} ;
- Layers in the lump, f_{lump} ;
- Overhang angle, α .

Figure 5 shows a schematic view of the different parameters tested on simulation parametric analysis. Another simulation output that was carefully studied is the simulation time. By maintaining the same meshing pattern, its fluctuation will have a more significant impact when applying a different f_{lump} .

The first parameter tested is the convection coefficient that emulates the powder, h_{powder} . The chosen values are 1, 5 and 15 [$\text{Wm}^{-2}\text{K}^{-1}$] while maintaining a T_{sink} equal to 100 °C, temperature chosen in order to share the same temperature as the baseplate.

Figure 6 shows the combination of results from parametric study A. It is possible to verify that the h_{powder} affects the slope behavior. On A1, where the heat extraction through convection is the smallest, it is possible to see a quasi-state of temperature stability. This would not fit the experimental

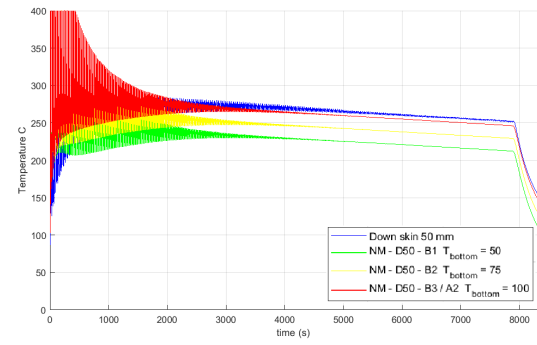


Figure 7. Temperature profile comparison of study B, between the experimental temperature Downskin (Blue) and the simulated temperatures.

results (Blue) since it is expected to have a slight temperature decay over time. Nevertheless, study A2 shares the same slope behavior as the experimental results. Study A3 has a steeper slope due to greater heat extraction through the geometry walls to the powder bed emulation. Therefore, the powder convection, h_{powder} , has a clear impact on the slope behavior, which is a great tool to help calibrate the model. However, to find the best h_{powder} , a method of trial-and-error was taken which can slow down the calibration process.

The second parameter tested is the baseplate temperature, T_{bottom} . The chosen values are 50, 75 and 100 [°C] of T_{bottom} while maintaining the rest of the parameters.

Figure 7 shows the combination of results from parametric study B. Changing the bottom temperature T_{bottom} , has an apparent effect on shifting the average temperature. A lower bottom temperature brings the temperature profile lower, but it does not visually impact the steepness of the temperature profile. On B3/A2, it was used at the highest temperature possible. Nevertheless, it would be possible to bring the simulated validation to a more excellent match if the $T_{\text{bottom}} > 100$ °C. However, this value would have been unreal compared to the actual experiment, where the imposed temperature was 100 °C.

With study B, it is possible to understand the role of the imposed temperatures on the baseplate during AM process. Looking at the final cooldown of each figure, B1 presents the highest cooling rate. This will have a considerable impact on the final part quality. The temperature gradient mechanism is responsible for generating residual stresses and giving special characteristics to the microstructure. Therefore, this numerical modeling allows us to understand the behavior of a selected temperature on the baseplate and, qualitatively, the deformation aptitude. In other words, if we know the final deformation at $T_{\text{bottom}} = 100$ °C, we know that any value chosen under it will have a higher deformation value.

In study C, instead of understanding the physical behavior by changing a parameter, now, it is a simulation parameter that suffers the change, in this case, the number of real layers into a modeling layer, having the name of f_{lump} . On this study, it no longer makes sense to compare with the experimental result, and our reference becomes the validated simulation (A2). The chosen f_{lump} values are 1, 2, 4, 8 and 16. The simulations results are shown in Figure 8.

Visually, it is possible to observe that the general trend is kept even when the f_{lump} is changed. As the number

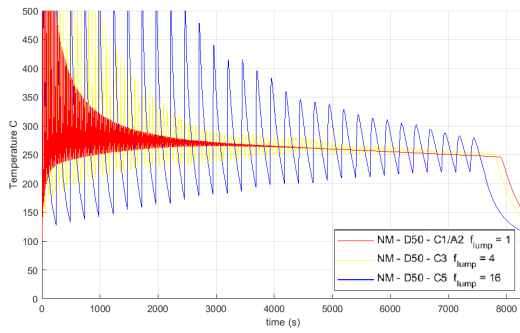


Figure 8. Temperature profile comparison of study C, between the validated simulation (D50 - C1/A2 Red) and the Downskin temperature of C3 and C5 simulations.

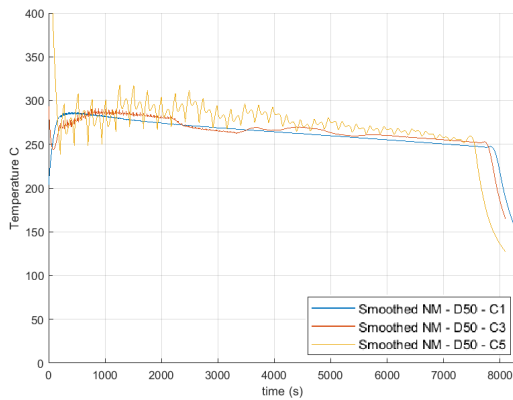


Figure 9. Smoothed temperature profile comparison of study C, between the validated simulation (D50 - C1/A2 Red) and the Downskin temperature of C3 and C5 simulations.

of lumping layers increases, the temperature fluctuation for each layer increases. This is due to prolonged step time for high lumping numbers. The model's purpose and desired precision determine the extent of lumping. The temperature data for lumping indicate that a greater number of lumped layers causes more significant oscillations. Despite the high value of lumping, the overall trend is nevertheless captured. Therefore, layer aggregation is a possible choice when the primary objective is to determine the overall temperature. However, history-dependent outcomes, such as microstructure evolution, cannot be predicted when the lumping technique is utilized because the local thermal history is not captured (13; 14).

To verify the correct agreement of average temperatures between studies, the Savitzky-Golay method was applied with a polynomial order of 4. The results are shown in Figure 9.

This method shows us the good agreement of all the studies to keep the general temperature trend, especially between C1 and C3.

Another goal of this study is to understand if sacrificing the local thermal history would bring advantages to simulation speed. Hence, Table 1 shows the different wallclock times of the simulations, where all the gray rows correspond to the validated simulation.

It is possible to verify that all the simulations with a f_{lump} of one have an average of 4 days and a half (4,525). It is still a considerable number for such a simple geometry

Table 1. Wallclock time of the studied simulations

Name	Wallclock time		
	Seconds	Hours	Days
A1	$3,55 \times 10^5$	98,61	4,1
A2	$4,24 \times 10^5$	117,78	4,9
A3	$4,15 \times 10^5$	115,28	4,8
B1	$3,56 \times 10^5$	98,89	4,1
B2	$4,19 \times 10^5$	116,78	4,8
B3	$4,24 \times 10^5$	117,78	4,9
C1	$4,24 \times 10^5$	117,78	4,9
C2	$2,11 \times 10^5$	58,61	2,4
C3	$1,30 \times 10^5$	36,11	1,5
C4	$1,29 \times 10^5$	35,83	1,5
C5	$6,74 \times 10^4$	18,72	0,8
E1	$4,13 \times 10^5$	114,72	4,8
E2	$3,58 \times 10^5$	99,44	4,1
E3	$4,24 \times 10^5$	117,78	4,9
E4	$4,01 \times 10^5$	111,39	4,6

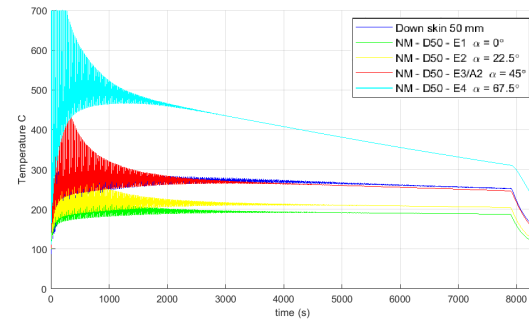


Figure 10. Downskin temperature profile comparison of study E, between the validated simulation (D50 - E1/A2 Red), the different overhang angles.

without complex overhangs or internal features. However, when observing the study C results, it is clear that increasing the f_{lump} significantly impacts the simulation time, whereas for a $f_{lump} = 16$, the simulation drops to less than one day. This could allow teams to optimize parameters and decide on the day after, thereby saving time and money. Another way to increase simulation speed would be having a coarser mesh or adding the minimal properties points into the simulation because fewer interpolation functions would be needed.

In the final study E, the parameter changed is α . This angle is measured from the Z axis, as shown in Figure 5. The chosen α values of the overhangs are 0, 22.5, 45 and 67.5 [°]. A temperature buildup will be expected on the down-facing or overhanging surface. This problem usually is fixed by adapting the input power or adding support structures. However, this increases the processing time and adds material that must be removed in post-processing, increasing the part's final cost. Figure 10 shows the simulation results.

It is possible to see that the steeper the geometry inclination, the greater the thermal accumulation effect. The E4 does not present the same horizontal behavior as the rest. This can mean that the result started not make physical meaning, which can be used as a pre-eliminatory study of the feasibility of an overhang. In other words, if the behavior of the temperature of a simulated object does not present

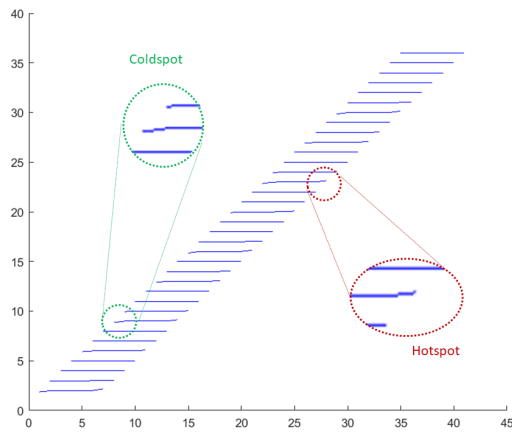


Figure 11. Line deviation representation of the simulation results.

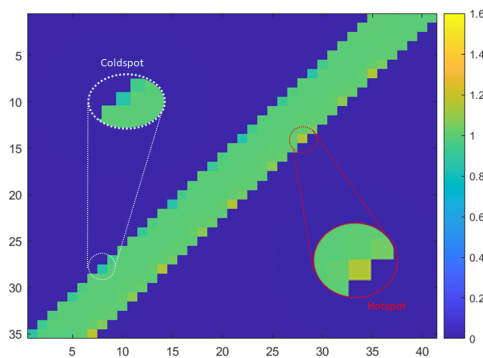


Figure 12. Color representation of the simulation results.

a slope lower than a certain amount, it is necessary the implementation of support structures in order to allow a healthy heat transfer.

However, changing the overhang angle does more than changing how heat accumulates. It also changes the surface area in contact with the powder bed. From the study E3 to E4, there is an increase of 85% of surface area in contact. Hence, the greater the angle, the more surface area is exposed to convection. Therefore, the vast surface area can explain the E4 effect of rapidly decreasing the temperature in contact.

Remarks

Besides developing a well-behaving thermal model, it was developed a mathematical to analyze and process simulation results. The developed code here has the capacity to extract all the node temperature information along the time from the simulation results. This could be used to cross information from the *in-situ* monitoring and the simulation to create a digital twin.

Nevertheless, in Figure 12, it is shown in a colored representation, where the lighter the color means that the temperature at that point is higher than the average of the layer's temperature. The opposite is also true. The darker, the lower the temperature at that point compared with the same layer. Important to say that the color bar does not have any physical meaning. The second approach, in Figure 11, instead of a color method, opted for a colorblind methodology, where each line represents a different layer where, for layer 20, if the value of the line is 20, it means that

that point shares the average of the layer. However, a higher value means that the temperature at that point overpasses the average and vice-versa. Therefore, in Figure 11, it is already possible to verify a slight deviation in each line at the beginning and end of each line. As expected, the left part of the line approximates the line under it. In contrast, the right part of the line approximates the line on top, meaning that the probability of a hotspot here is higher than in the opposite part.

Conclusions

Most of the actual modeling approaches are still far from the actual capabilities of the AM machines. Simulations are still limited to some extent in their geometry and complexity. Research indicates that process parameters have a considerable effect on L-PBF component quality. Consequently, the developed thermal model could incorporate a Design of Experiment (DoE) research to collect important information on optimizing the process parameters and enhancing the quality of the final components. While an experimental DoE may incur additional expenditures for the organization, a numerical DoE conducted using simulations saves those costs. This project demonstrated that accurate models could be created to estimate the temperature development during the manufacturing process, from which most of the component's final attributes are obtained. This is an important achievement in this industry since it will ultimately result in fewer discarded parts owing to mechanical faults and lower expenses connected with AM procedures, particularly MAM.

The main conclusions that were reached are presented below:

- With the part-scale thermal model, it is possible to capture the overheating effect and build-up temperature along the manufacturing process, which generate hotspots;
- In the parametric study, the powder convection coefficient had the most significant impact on the steepness of average temperature along the process. In contrast, the imposed temperature at the bottom of the baseplate has the power to shift the temperature profile, maintaining the general slope completely. The hotter the bottom temperature, the higher the average temperature was during the process. This will have a direct impact on the thermal gradient mechanism, hence, influencing a possible residual stress study;
- By neglecting the meso-scale physics and implementing a layer-by-layer approach into a part-scale model, it is possible to gain MAM simulation speed with the inherent cost of losing the local thermal history but maintaining the average temperature trend.

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