# HEAT TRANSFER FINITE-ELEMENT ANALYSIS OF ADDITIVE MANUFACTURING BY BLOWN POWDER. A METHODOLOGY FOR A PARALLEL ALGORITHM

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**Abstract.** Additive manufacturing processes are being increasingly implemented in many industrial sectors, thanks to recent advances that allow for reduced costs and lower production times. As a result, there is a strong demand of a software ecosystem to support the design with these technologies, including tools for finite-element analysis. However, the computational cost associated to this finite-element simulations is rather high, because of nonlinearities and transient phenomena. This work aims to overcome this with high performance computing techniques. More precisely, a methodology to transform a serial algorithm for the heat transfer analysis of additive manufacturing by blown powder with a domain decomposition technique is presented. Verification of the new implementation against the existing one will show if the selected approach is useful and can be also adopted for the associated mechanical problem.

## 1 INTRODUCTION

Additive Manufacturing (AM), also known as 3D printing, refers to a family of processes that build up a three-dimensional object layer-by-layer from a Computer-Aided Design (CAD) model.

AM processes are opposed to Subtractive Manufacturing processes, such as machining, not only due to their different basis, but also because they are competitive for different end products. More precisely, AM is advantageous for pieces with a very complex geometry, design of customized unique items, and production in small batches.

Recent advances in this technology have allowed for reduced costs of production and increased printing speeds. For this reason, AM is already beneficial for many industries, including the aerospace, automotive, dental, medical, and consumer goods sectors.

Market researchers predict an exponential growth of the AM market in the next years. As a result, there is an increasing need of Computer-Aided Technologies (CAx) to support AM processes and machines, including Finite-Element Analysis (FEA).

Different AM technologies have already been modelled with FEA, often taking advantage from previous experience acquired in modelling welding processes ([1, 2, 3]).

This work focuses on the thermal analysis of *blown powder* or *powder feeding* technologies for metal components. In this type of processes, metal powder is blown coaxially to a laser beam that melts the particles on a substrate to form a metallurgical bond when cooled.

A numerical simulation and experimental calibration for the heat transfer analysis of additive manufacturing by blown powder technology has been recently carried out with successful results [2] . However, dealing with the computational cost of the simulation is still an open question.

The purpose of this work is to address this unsolved problem with a strategy to transform the serial implementation devised in [2] into a parallel one, that can run in a High-Perfomance Computing (HPC) facility.

A parallel algorithm will be able to solve for larger problems without lost of resolution and with reasonable simulation times. This will be practical for the Industry mainly for two reasons:

On the one hand, the simulation of larger components will no longer be limited by the computational complexity. Likewise, it will be possible to deal with optimization problems, such as finding the printing sequence that minimizes distortions, residual stresses and hot-cracking risk of the piece.

The remaining of the paper only explains the methodology followed. Section 2 reviews the continuum and weak formulations of the heat transfer problem for AM by blown powder technology. Section 3 introduces the particularities of a parallel finite-element approximation. Section 4 describes a step-by-step process to parallelize the algorithm developed in [2] . Finally, some conclusions are drawn in Section 5.

## 2 HEAT TRANSFER ANALYSIS OF AM BY BLOWN POWDER

A typical setting for 3D printing by powder feeding consists of a metal substrate clamped to a supporting structure, as shown in Figure 1. According to this, let $\Omega_t$ be an open bounded domain in $\mathbb{R}^3$. During the deposition phase, the domain is heated by the moving laser and grows in time from $\Omega_i$ to $\Omega_f$. That motivates the use of the subindex $t$. Afterwards, the domain remains constant and it cools down to the initial temperature.

Both the heating and cooling phases of the process are governed by the equation of conservation of energy. In terms of the enthalpy, instead of the internal energy, the local differential form of this equation reads

$$\dot{H} = -\nabla \cdot \mathbf{q} + \dot{Q} + \dot{D}_{mech}, \quad \text{in } \Omega_t, \tag{1}$$

where $\dot{H}$ is the enthalpy rate, $\mathbf{q}$ is the heat flux due to heat conduction, $\dot{Q}$ represents the source term, and $\dot{D}_{mech}$ is the thermo-mechanical dissipation rate. All terms in Equation 1 are per unit volume.

For this process, the heat source is the energy input from the laser beam, that is very concentrated and moves according to a predefined deposition sequence, more commonly known as the *scanning path*. On the other hand, the thermo-mechanical dissipation can be neglected, in front of the energy input.

The power of the laser beam is able to melt the powder stream, together with the particles on the surface of either the substrate or previously deposited layers, and creates a localized melt pool. The melt pool advances with the laser beam and the material left behind quickly solidifies.

This phase transition is accounted for in the governing equation by splitting the enthalpy rate in terms of the temperature, $T$, and the latent heat rate, $\dot{L}(T)$. Hence, the enthalpy rate is written as

$$\dot{H}(T, f_L) = C\dot{T} + \dot{L}(T), \tag{2}$$

where $C(T) = \partial H/\partial T$ is the temperature dependent heat capacity. More details regarding the modelling of the phase transformation can be found in [2] .

The heat introduced by the laser into the system is transferred from regions at a higher temperature to regions at a lower temperature through heat conduction. According to Fourier's law, the heat flux (per unit area) associated to this phenomenon is proportional to the gradient of temperature:

$$\mathbf{q} = -k\nabla T, \tag{3}$$

where $k(T)$ is the temperature dependent thermal conductivity. Due to the high conductivity of materials, this is the predominant mode of heat transfer in the process.

Assuming a split of the smooth boundary as $\delta\Omega_t = \Gamma_T \cup \Gamma_q$, where boundary conditions are enforced as either prescribed temperature on $\Gamma_T(t)$ or prescribed heat flux on $\Gamma_q(t)$, and given suitable initial conditions in terms of a known temperature field $T(t=0) = T_i$, the weak form of Equation 1 is written as

$$\int_{\Omega_t} \left( C\dot{T} + \dot{L}(T) \right) \delta T \ \mathrm{d}\Omega + \int_{\Omega_t} k\nabla T \cdot \nabla(\delta T) \ \mathrm{d}\Omega = W^{ext}_{ther}, \quad \forall \delta T, \tag{4}$$

where $\delta T$ are the test functions compatible with the Dirichlet boundary conditions, and $W^{ext}_{ther}$ denotes the external work of the thermal loads, expressed as

$$W^{ext}_{ther} = \int_{\Omega_t} \left( \dot{Q} + \dot{D}_{mech} \right) \delta T \ \mathrm{d}\Omega + \int_{\Gamma_q} \left( q_{cond} + q_{conv} + q_{rad} \right) \delta T \ \mathrm{d}\Gamma, \quad \forall \delta T. \tag{5}$$

As seen in Equation 5 heat is released through the boundaries of the domain through conduction, convection and radiation.

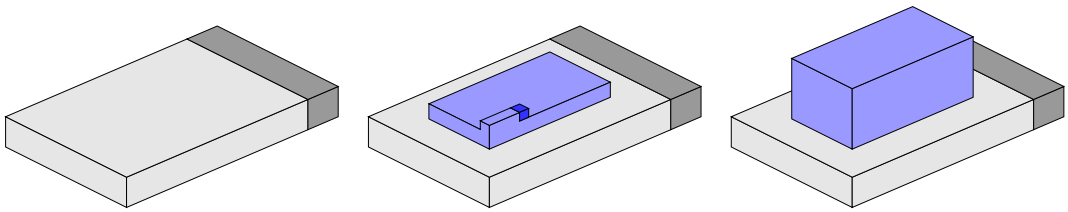



**Figure 1**: Initially, the computational domain consists only of the substrate $\Omega_i$, that is clamped to a supporting system (dark gray). During the heating phase, the domain, now denoted by $\Omega_t$, grows according to the metal deposition sequence. The dark blue area indicates where the heat source is focused and contains the melt pool at time $t$. The energy input is transferred from this small region to the remaining body through heat conduction. Once the printing is finished, the substrate and the printing $\Omega_f$ cool down to the initial temperature. Heat conduction drives the heat loss through the clamped material surface. Elsewhere, heat convection and radiation govern the heat loss with the surrounding air.

At the contact surface between the substrate and the clamping system, heat is exchanged by conduction according to Newton's law,

$$q_{cond} = h_{cond}(T - T_{clamp}), \tag{6}$$

where $h_{cond}(T)$ denotes the temperature dependent Heat Transfer Coefficient (HTC) by conduction and $T_{clamp}$ is the temperature of the clamping system.

Otherwise the material surface releases heat into the surrounding air by a combination of heat convection and heat radiation. In this case, the heat loss is also expressed with a Newton's law as

$$q_{conv} + q_{rad} = h_{comb}(T - T_{air}), \tag{7}$$

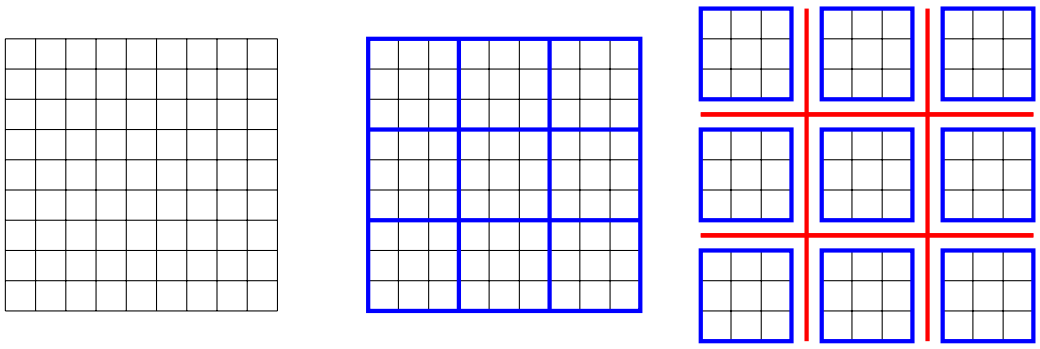
where $h_{comb}(T)$ is the HTC for the combined effect of convection and radiation. To apply this boundary condition, a search algorithm is needed to know the boundary of the domain at each time step.

## 3 FINITE-ELEMENT APPROXIMATION IN A PARALLEL SETTING

In order to solve the heat transfer problem in a shared-memory or distributed-memory multiprocessor computing system, the finite-element approximation is coupled with a domain decomposition (DD) technique.

A DD method for parallel computing consists of an overlapping or non-overlapping decomposition of the space discretization. The mesh associated to the global problem (of size $N$), is split into as many local meshes as processors ($P$), as represented in Figure 2. Thus, the local size of each problem is of the order of $N/P$.

With DD methods, the local integration and assembly of the finite-element mesh can be easily done in parallel. Afterwards, the global system of equations can be solved either



(1) Global problem (2) Mesh partition (3) Local problems

**Figure 2**: Schematic representation of a non-overlapping domain decomposition for a uniformly structured 2D grid. Blue lines represent the boundaries of the local problems, integrated and sub-assembled at each processor. Red lines represent the global interface, where the nodes are shared among different processors.

with a preconditioned iterative scheme or a sparse direct solver, such as PARDISO, the one employed in this work.

## 4 FROM A SERIAL TO A PARALLEL ALGORITHM

The diagram shown in Figure 3 describes the strategy that will be followed to design a parallel algorithm from the serial one developed in [2] . With this stepwise process the complexity of the problem is increased gradually, by adding a new nonlinearity or a new transient phenomenon.

The first step of the process is the linear and well-known three-dimensional Poisson problem. The parallel implementation will be verified against the serial implementation, by comparing the solutions obtained for a simple benchmark problem.

This reference problem consists of a unit cube, with Dirichlet boundary conditions at the bottom side to represent the contact with the clamping system, Neumann boundary conditions at the lateral sides representing the heat exchange with the surrounding air, and Neumann boundary conditions at the top side to represent the external source term. In later stages, this example will be duly modified to account for the new characteristics of the model.

## 5 CONCLUSIONS

This work presented a methodology to parallelize a serial algorithm for the numerical thermal analysis of an additive manufacturing process by blown powder technology.

The formulation of the associated heat transfer problem showcased the challenges of the numerical simulation, that can be classified in two groups: transient phenomena (growing domain that follows a moving heat source) and nonlinearities (phase change and

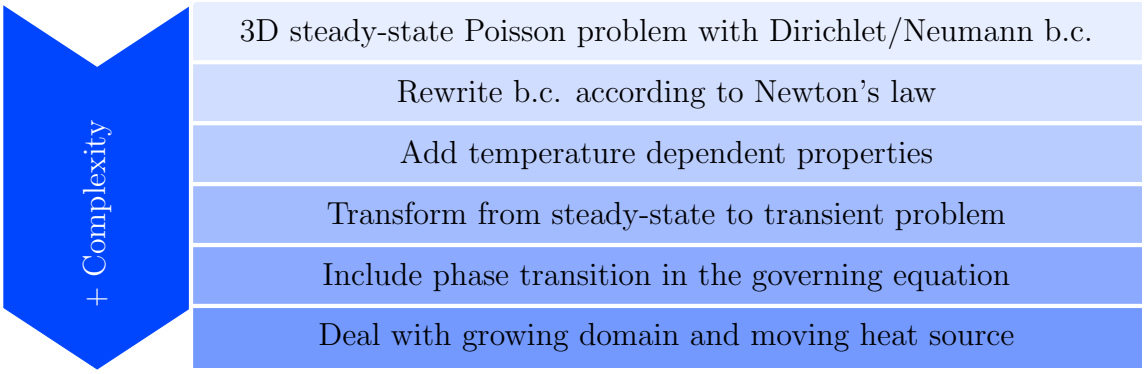



**Figure 3**: The proposed strategy for developing the parallel algorithm starts from solving a linear and well-known problem, the 3D Poisson problem. New characteristics are incorporated step-by-step into the numerical model, until reproducing the heat transfer analysis formulated in Section 2.

temperature dependence of the material properties).

This motivated a stepwise procedure, that allows to deal gradually with the complexity of the problem in a parallel scenario. Future work will determine whether this approach gives successful results and can also be useful for the parallelization of the associated mechanical problem.

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