Simulation based optimized beam velocity in additive manufacturing

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Abstract. Manufacturing good parts with additive technologies rely on melt pool dimension and temperature and are controlled by manufacturing strategies often decided on machine side. Strategies are built on beam path and variable energy input. Beam path are often a mix of contour and hatching strategies filling the contours at each slice. Energy input depend on beam intensity and speed and is determined from simple thermal models to control melt pool dimensions and temperature and ensure porosity free material. These models take into account variation in thermal environment such as overhanging surfaces or back and forth hatching path. However not all the situations are correctly handled and precision is limited. This paper proposes new method to determine energy input from full built chamber 3D thermal simulation. Using the results of the simulation, energy is modified to keep melt pool temperature in a predetermined range. The paper present first an experimental method to determine the optimal range of temperature. In a second part the method to optimize the beam speed from the simulation results is presented. Finally, the optimized beam path is tested in the EBM machine and built part are compared with part built with ordinary beam path.

1. Introduction
The quality of metallic parts manufactured with additive technologies is highly related to melting strategies. Melting strategies means beam trajectories and characteristics such as speed, intensity and focus. These strategies are based on simple trajectories built on contour and hatching strategies filling the contours at each slice. Beam characteristics are determined from simple thermal models to control melt pool dimensions and temperature and ensure porosity free material. These models take into account variation in thermal environment such as overhanging surfaces or back and forth hatching path. However not all the situations are correctly handled and precision is limited. This paper proposes new method to determine energy input from full built chamber 3D thermal simulation. Using the results of the simulation, energy is modified to keep melt pool temperature in a predetermined range. The paper present first an experimental method to determine the optimal range of temperature. In a second part the method to optimize the beam speed from the simulation results is presented. Finally, the optimized beam path is tested in the EBM machine and built part are compared with part built with ordinary beam path.
Literature review
Numerous studies deal with the simulation of powder bed additive manufacturing process. [1–3] proposes thermal simulation of the electron beam additive manufacturing process based on a finite element model. [4–7] propose it for laser additive manufacturing. These models are then used for predicting the thermal stress and deformations or the size of the melt pool. [8] has used these models to predict the effect of support structure on thermal deformations and proposes new support strategies. [9] used this model to predict the size of a built strut in EBM and thus improve dimensional accuracy. [10,11] proposes a simulation of the process based on a Boltzmann lattice model where the scale of the study is the powder grain (50 μm). This study aims to better understand the EBM process on a microscopic scale and to make recommendations in order to better master the process. They also used their simulation to optimize the hatching strategy in EBM as presented in [12]. These models are effective to simulate millimeters of trajectory. However, the simulation of a complete manufacturing entity requires simulating several meters, or kilometers, of trajectory. The finite element simulation is suitable for the understanding of the process. However, a faster simulation would allow to increase the size of the simulated volumes and thus could be used to assist in the choice of the manufacturing parameters or their optimization. This is why a new simulation was developed based on different principles as proposed by [13].

Figure 1. Temperature along a melted line, comparison between Abacus and Finite Element

The founding idea of abacus simulation [13] is to see the simulation of a complete case as the succession of standard cases. The standard cases are the heating and cooling of the material under a fixed electron beam. From these standard cases, graphs of evolutions of the temperature of the different points of the 3D space are generated. They store the variation of the temperature of the points around the beam center as a function of the beam parameters and the position of the point relative to the beam center. The displacement of the electron beam is modeled as an electron beam remaining fixed for a time step and then moving to the next point. At each time step, the evolution of the temperatures of the material is known thanks to the charts calculated with a fixed beam. The results obtained using Abacus simulation has been compared to results from finite element simulation as proposed by [1,2]. Figure 1 shows a temperature distribution along a line swept by the beam. In this case the beam has traveled from X=0 to X=4 mm and the picture is taken when the beam is at X=4mm. This figure shows limited difference between FE considered has the reference and abacus that needs to prove its reliability. Comparison with experimental results would have been better but no data exists to make it as measuring temperature distribution in an EBM machine is still an unsolved issue. Based on comparison with FE results the abacus simulation has been considered has precise enough to develop simulation based melting strategy optimization.
3. Determination of the optimal range of temperature

![Sample disc melting trajectories](image)

**Figure 2.** Sample disc melting trajectories

The abacus based simulation proposed by [13] provides the temperature distribution over the built part. This temperature must be controlled no only to limit thermal distortion and porosity. Thermal distortion is a consequence of overheating and porosity of under heating. It is thus necessary, to later create optimal beam path, to determine the optimal temperature range. In order to establish this link, a disc of radius 8 mm and thickness 5 mm is manufactured. The beam trajectory used is composed of 79 concentric circles as shown figure 2 and the melting parameters (speed, current, focus) are kept constant along the path. The built of the disc is simulated using the abacus based simulation and the temperature distribution along the disc radius is given figure 3. The circle becoming smaller at the center, the temperature reached at the center is higher than for the external zones.

![Temperature and porosity along disc radius](image)

**Figure 3.** Temperature and porosity along disc radius

This part is then manufactured and a section is cut to be analyzed using tomography. Figure 3 shows a view of this section and the porosity measured along the radius from the tomography results. A correlation between the maximum temperature reached and the porosity rate can be observed and four areas can be distinguished:

- The unmelted zone where the temperature of the material did not exceeds 1665 °C.
The area where the material is molten but porous. It corresponds to temperatures between 1665 and 2700 °C. However, there is no correlation between this temperature and the porosity rate, only the presence of porosities can be predicted.

The area where the material is not porous. It corresponds to temperatures between 2700 and 2760 °C. Here, the material is correctly melted and the number of porosities is minimal.

The central area where the temperature exceeds 2760 °C, the rate of porosities is minimal but a shape defect of the upper surface of the disk is observed. This is why this zone is considered overheated. The upper surface of the workpiece seems to be correlated to the excessive temperature reached.

Looking at these results, the optimal range of temperature is determined as being between 2700°C and 2760°C.

4. Simulation based optimal beam path

Most of the melting strategies are determined using very simple thermal models. Having a full 3D process simulation allows using simulation-based optimization method as proposed by [14] to optimize the different parameters of the fusion strategy. For the optimization of EBM melting strategies, the method is built on successive steps. First, an objective function is defined: in the current case study, all points of the last manufactured area have to reach a maximum temperature between 2700 and 2760 °C. Then the optimization parameters are defined: for the EBM process beam trajectory and beam parameters along the trajectory are considered. Then for each time step:

- The melting strategy parameters are optimized based on the results of the previous time step simulation. The optimization function provides new parameters (beam current, beam focus and new beam position) for the current time step to comply with the objective function. The optimization is based on thermal result from the previous time step (t-dt). It modify the energy input for the current time step to control the temperature range based on the principle of automatic control.

- The process is simulated with the new parameters and a new heat map for the current time step (t) is calculated. The temperature reached by the current beam center at the current center will be used for the next time step melting strategy parameters optimization.

This method makes it possible to define the melting parameters at time t (position and parameter of the beam) based on the temperatures reached at time step t-dt and the target temperatures set. The optimization function therefore acts as a servo function of the melting strategy over time depending controlling the temperatures reached. The trajectory followed during the simulation will thus respect the thermal criteria and can then be used for manufacturing.

One of the advantages of this method is the separation of manipulated objects:

- Simulation of the process.
- Optimization function: in the following example, a simple optimization function will be proposed but the search for the best optimization function is a scientific challenge as such. Indeed, the thermal phenomena involved are highly non-linear and multi-variable.
- Objectives: in the following example the quality criteria defined above have been used, however, if the objectives in terms of quality change, these could be modified without affecting either the simulation or the optimization function. For example, for certain applications such as heat dissipation, the presence of porosity in the material may be allowed. In other cases, a high geometric quality will be required but porosities will be tolerated. The target temperature will then be modified but this won’t affect the simulation or optimization module.

Such an environment allows a great flexibility in terms of objective, optimization function and simulation.
5. Case study

Table 1. Melting parameters

| Parameter              | Value |
|------------------------|-------|
| Focus Current          | If    |
| Initial speed (mm/s)   | V     |
| Beam voltage (kV)      | U     |
| Beam current (mA)      | I     |
| Layer thickness (µm)   | h     |
|                        | 4     |
|                        | 980   |
|                        | 60    |
|                        | 5     |
|                        | 50    |

For the case study the goal is to determine the optimal strategy to melt a prismatic part as represented figure 4. In the first approach, the trajectory is fixed as well as the beam current and beam focus. Only the beam speed along the path is modulated to control the temperature reached. The trajectory used is a simple hatching as represented figure 5 and the beam parameters are given table 1. The optimization function will increase the speed if the temperature gets too high and will come back to the initial speed if the temperature is too low. The proposed function varies the speed along a predefined path in order to meet the quality criterion. The objective is to stay in the optimal temperature range between 2700°C and 2760°C. For this, a target temperature $T_{target}$ was set at 2730°C i.e. the middle of the optimal temperature range. The speed variation is then calculated based on the maximum temperature at the previous time step $T_{max-dt}$. Three cases are distinguished:

- If the temperature is below the threshold temperature set at 96% target temperature, i.e. 2620°C, the speed is set to the initial speed ($InitialSpeed$).
- If the temperature is between the threshold temperature and the target temperature, the speed is increased and a new speed ($Speed$) is calculated using equation (1).
- If the temperature is above the target temperature, the speed is increased such that the next simulated point is far enough and that the hottest point is no longer in the heating zone of the beam determined by the simulation.

\[
Speed = \frac{(T_{max-dt} - T_{target})^2}{0.072} \times InitialSpeed
\]

Figure 4. The case study part

Figure 5. Melting trajectory for the prismatic part

The map of maximum temperatures reached resulting from the optimized melting strategy is shown in figure 6. This map can be compared with the maximum temperature reached with a constant speed equal to the initial speed and represented figure 7.
In order to have a finer analysis of the temperature distribution with or without optimization, the distribution of the voxel percentage as a function of the maximum temperature reached is plotted figure 8 for the constant speed strategy and figure 9 for the optimized strategy. Without optimization, the average temperature reached on the melted zone is 2596 °C whereas it is 2600 °C with optimization. This difference is not significant. On the other hand, the temperature distribution is substantially different. Without optimization (see figure 8), only 20.4% of the voxels in the melted zone reached a correct maximum temperature (between 2700 and 2760 °C). With the optimization (see figure 9), 57.0% of the voxels in the melted zone reached a correct maximum temperature. Even if this percentage can be further improved, the number of voxels likely to generate porosity or a defect in shape is thus greatly reduced by the use of a very simple optimization function.
Figure 10 shows that the speed of the beam increases when the beam passes back into an area already heated. This happen after a U-turn at the beginning of a new line. In this case the speed is increased from 1 to 1.2 m/s to avoid over heating of zone just exposed to the beam at the end of the previous scanned line. The speed is also increased when the lines are shorter near the top of the triangle. For example the line at $y = 7.3$ mm has a length of 0.6 mm. For this line, the average beam speed is 1.154 m/s as shown figure 11. For the line near the base of the triangle at $y = 0.7$ mm and of length 14 mm, the average speed is 1.037 mm/s as shown figure 10. Close to the top of the triangle, the melted lengths are decreasing and the beam therefore returns more and more rapidly to areas already heated. Its speed must therefore be then increased to avoid overheating. Using simulation based melting strategy prevents overheating of the material while ensuring a minimum heating in order to avoid porosities.

**Figure 10.** Speed along a long line

**Figure 11.** Speed along a short line

**Conclusion**

Defining optimal melting strategies is a key factor of part quality in additive manufacturing. This supposes first to be able to determine the key physical parameters. Then the relation between the melting strategies and these key parameters have to be established. These two conditions being met, it becomes possible to predict the optimum melting conditions.

Chapter 3 of this paper highlighted the link between the temperatures reached by the material and its quality. Thus, recommendations on the temperatures to be reached in order to avoid defects in shape but also the porosities was stated and can be considered of the key physical parameter of part quality.

In chapter 4, a simulation-based optimization module was proposed to generate melting strategies that met the stated recommendations. In this paper a very simple optimization algorithm was used. Nevertheless, improving this algorithm, including more complex correction strategies, would allow to better meet the thermal criteria defined and further improve the parts quality. Moreover, in the long run, the optimization function should be able to optimize all the parameters of the fusion strategy and not only the speed of advance as is the case here. This also includes the trajectory followed by the electron beam.

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