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DEFECTS LOCATION ESTIMATION USING MULTISCALE THERMAL FINITE ELEMENT METHOD

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Abstract: The Selective Laser Melting (SLM) process is the subject of numerous researches for a few decades. Manufactured parts experience very high heating and cooling rates along the laser beam path and suffer an extensive range of temperatures. These high heating and cooling rates can lead to defects such as cracks, distortions, and porosities. These defects are driven by the thermal history, related to several factors such as scanning strategy, surrounding powder insulation, parts geometry, number of parts to be manufactured, recoating time, etc. All these factors need to be considered to precisely simulate the thermal history. In this study, a multiscale thermal approach has been developed and applied to a study case. Most of the thermal history aspects are covered using five temporal and spatial scales FEM model. The overall thermal history and future improvements for simulating a full build plate in reasonable computational time are discussed.

1 INTRODUCTION

The Selective Laser Melting process is a metal additive manufacturing process widely adopted in the industry and research fields since the last few decades. It consists of scanning a thin (tens of microns thick) metal powder layer using a high-power laser heat source. The process's attractiveness relies on its ability to generate highly complex geometries from materials that could be challenging to manufacture otherwise. This flexibility allows the manufacturing of lightweight, functional industrial parts of elevated added value.

However, there remains some cost and technical challenges to tackle for wider industrial adoption of the process, including the prediction of porosities, distortions, and residual stresses generated from the extremely high heating and cooling rates [1].

The computation of the thermal history requires a strict consideration of the numerous phenomena occurring during the manufacturing process at different scales, i.e. the scanning strategy, the layering delay, the heat accumulation due to the part geometry and complete build plate, etc. These aspects affect the thermal fields that influence regions' heating and cooling rates along the laser beam path.

Several methods could have been used to simulate the thermal history of the SLM process, such as adaptative mesh schemes [2], superposition approaches [3], use of GPU hardware to accelerate the computation [4], and multiscale approaches [5].

Multiscale approaches usually consider the thermal aspects at the scanning-track or layer scale only [5]. These thermal outputs are then used in the thermomechanical resolution [6]. However, the previously mentioned thermal aspects could not be fully captured if every scale from macroscale to microscale is not considered. Recent works have shown a correlation between the temperature attained locally and the distribution of porosities within the part [7]. Hence, simulation of thermal history may be directly used to predict location of such defects.

In this study, a novel multiscale approach is presented. It links the thermal outputs of five distinct scales together. Each scale is described and the captured thermal aspects as well as the heat sources' modeling assumptions are listed.

2 MULTISCALE APPROACH DESCRIPTION AND STUDY CASE

The multiscale approach comprises five conjugate spatial and temporal levels. Each scale passes the computed thermal data along to the next.

An industrial part, which has been the subject of a previous research paper [8], was chosen as a study case. The part is an hydraulic join used in the aeronautic industry and can be seen Figure 1a, as a topologically optimized shape, machined on functional surfaces. The FEM model was realized using ABAQUS CAE 2018 FE package.

The main reason for using a multiscale approach comes from the wide range of temporal and spatial resolution required to capture all thermal phenomena and all lasing strategy parameters. Table 1 lists the spatial and temporal domains for each scale and Figure 2 shows the overall multiscale approach from macroscale to microscale.

Table 1: Temporal and spatial domains of each level

Level	Temporal domain	Spatial domain		
1 (Parts)	Days	100mm	100mm	100mm
2 (Layer)	Minutes	100mm	100mm	1mm
3 (Chessboard / Stripes)	Seconds	1mm	1mm	0.1mm
4 (Scan track)	0.01 second	1mm	0.1mm	10µm
5 (Melt pool)	0.1 millisecond	10µm	10µm	10µm

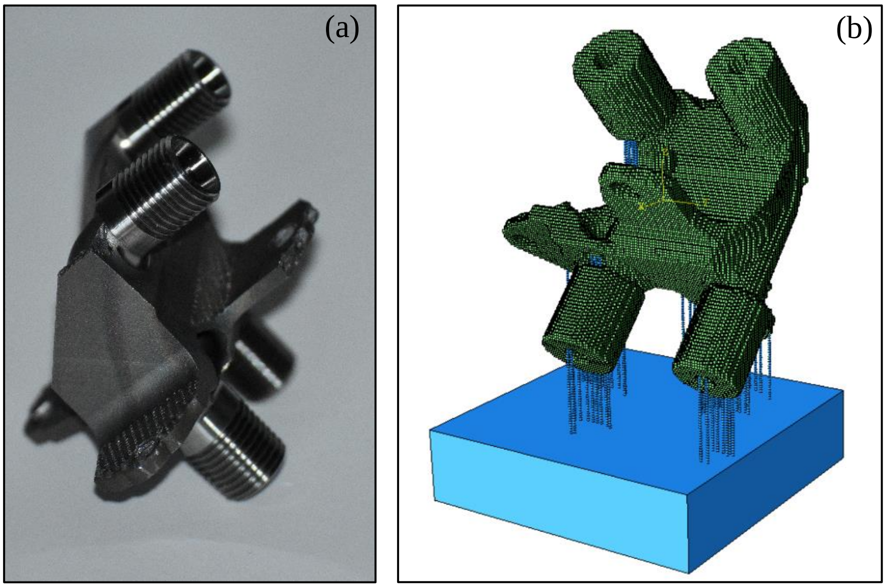

Figure 1: Original industrial hydraulic join (a) and hydraulic join ABAQUS model, supports and build plate (b)

2.1 Level 1 description

The first level is the whole build-plate scale. It includes each part of the build to be manufactured. Its main objective is to provide an overview of the thermal diffusion within the parts, identifying partially insulated areas according to the heat fluxes coming from the upper layer, and evacuated through the supports and the build plate.

The parts are discretized with voxel elements at the height of the macro layers. Macrolayers are a bundling of several building layers. The thermal exchanges with the surrounding powder are considered small, considering the high difference of thermal conductivity between solid and powder materials. Hence, to avoid a fine mesh of the powder a small convection coefficient has been used on the lateral faces of the parts and the supports, as a first rough approximation.

The parts are attached to the build plate by the support structures. A prescribed temperature is set at the build plate's lower surface.

Primarily, the voxels are all deactivated, then consecutively activated and heated layer-wise using a volumetric heat source for a duration corresponding to the total duration of all layers within the macro layers.

The heat injected at the top of the activated regions is dissipated by the conduction within the underlying solid regions through thermal conduction transfer. Insulated regions (such as unsupported or overhang regions) suffer a temperature rise due to heat accumulation.

The computed thermal fields are then observed step by step. Regions of maximum or minimum temperatures can be registered and selected for further analysis at the second level.

2.2 Level 1 results

The part is 67 mm high, at a distance of 10 mm on a reduced build plate. This is a reduced model developed here as an example of the multiscale method. Level 1 geometries, comprising the part, the supports, and the build plate, are shown in Figure 1b.

For sake of simplicity, each step duration was calculated to scan throughout all the physical layers within each macro layer. A more precise scanning time could have been considered using real production duration.

The heat source considered delivered volumetric energy for each macro layer as represented in Figure 3a.

Isotropic aluminum temperature-independent material properties were considered as a first approximation. The USDFLD Abaqus subroutine was used to change the material properties during each activation, and to set the new macro layer temperature at the underlying body’s temperature.

Level 1 results at macro layer n°47, which is the one where the highest temperature is reached during the build, are shown Figure 3b.

This upper macro layer, which reaches a maximum temperature of 720°C, is thus identified and further investigated at Level 2.

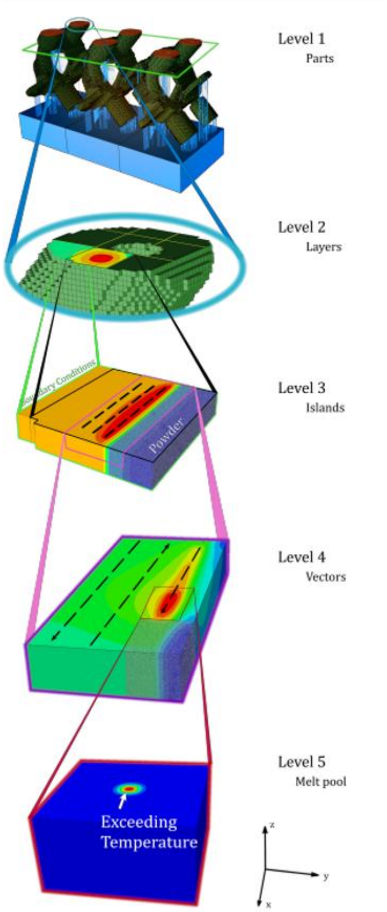

Figure 2: Overall multiscale approach

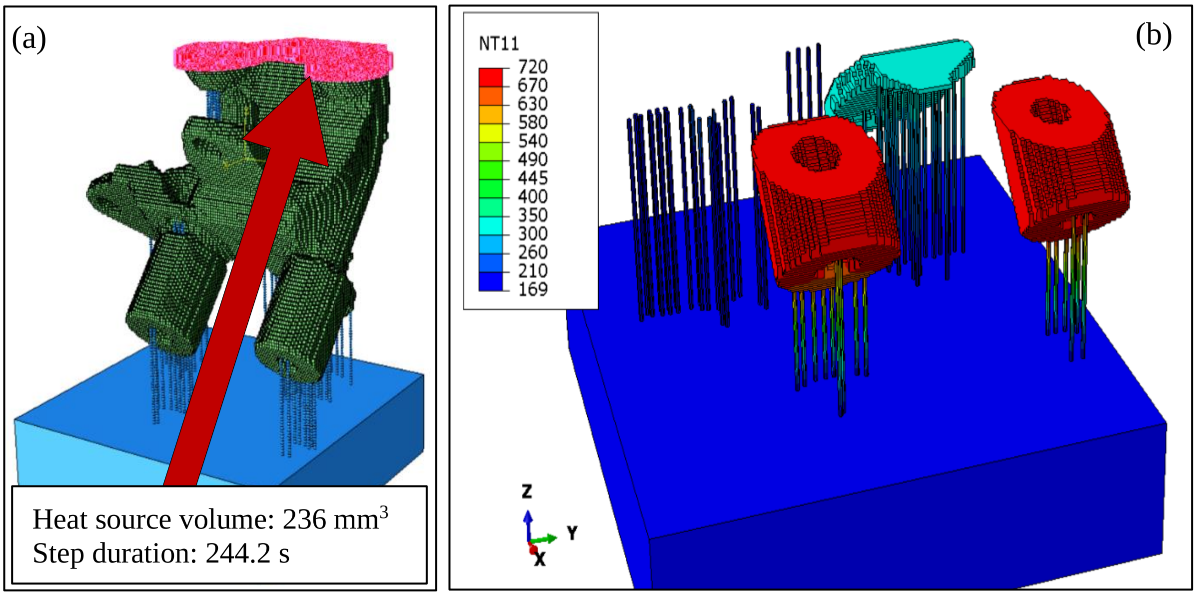

Figure 3: Level 1 model at (a) a random heated macrolayer, and (b) maximum temperature results at macrolayer 47

2.3 Level 2 description

The second level must be performed for each region identified by the user at the build-plate scale (Level 1), or to pre-defined typical zones, known to be problematic, such as isolated thin walls or lattices structures zones.

Level 2 is a zoom on specific layers identified at Level 1, or typical zones known to need accurate study, modeling a physical layer on top of the previous macro layer, heated with stripes or islands patterns (according to the scanning strategy).

This level's objective is to observe the impact of the scanning strategy (island, stripes, etc.) by heating a particular sequence of islands on the layer.

The layer computed thermal history is looked upon to identify the island or the stripe where the maximum or minimum temperature is reached. Depending on the exact island locations and the scanning sequence, it is expected to reach different maximum temperatures for different sequence, and possibly to be able to optimize the heating sequences. This area's thermal fields are recorded and further investigated at Level 3 if necessary.

2.4 Level 2 results

Level 2 models the supports and the part up to the macro layer identified at Level 1. The rest of the part and the build plate are deactivated as considered non useful to impact the local behavior.

A temperature boundary condition of 180°C (computed at Level 1) was set, here at the support base, since the Level 1 results showed that this temperature did not vary significantly during the macro layer heating. The optimal dimension of this sub model is also evaluated analytically and has been confirmed by several comparative simulations.

Surface heat flux loads were applied at the top surface of the macro layer (see Figure 4a). These loads' size and geometry correspond to a chessboard scanning strategy in this study case. All islands were heated sequentially, according to a typical chessboard sequence, and the zone with the maximum temperature (see Figure 4b) was chosen for deeper analysis at Level 3 modeling. Other scanning strategies, such as a stripe scanning strategy, could have been studied likewise, and even compared.

Figure 4 shows both the Level 2 model with an island-like loading, and the maximum temperature island result. This island will be zoomed in at Level 3.

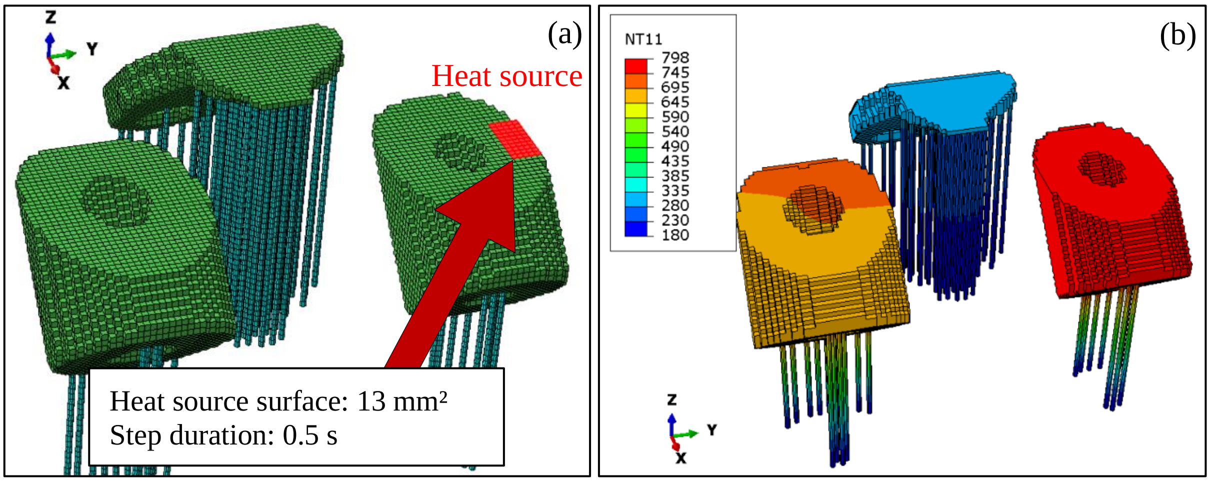

Figure 4: Level 2 model with (a) an island-like heat source displayed, and (b) maximum temperature results from a particular island sequence

2.5 Level 3 description

Level 3 is a zoom of the Level 2 identified region where a too high, or too low temperature is attained. Level 3 models a particular island or stripe and models the whole scan tracks' heating, as several lineic heat sources applied subsequently throughout this region.

The temperature fields far from the island of interest, computed at Level 2, are used in Level 3 as boundary conditions to reduce the geometrical domain.

With Level 3 computed thermal history, it is possible to identify the scan track which has suffered the maximum temperature and to compare various scan directions and the use of contouring strategies. This scan track zone will be further studied at Level 4, if needed.

2.6 Level 3 results

Level 3 model is a zoom on the zone identified at Level 2, and surface heat flux loads are applied subsequently on the upper surface. The shape of each load represents whole laser scan track lines.

Compared to Level 2, the model geometry was further reduced because at this time scale temperature variations are negligible outside this modelled zone (see Figure 5). The time increments and the meshes were both refined in comparison to the previous level.

Two sequences were tested: left to right and right to the left island-like loadings. Other sequences such as up to bottom and diagonals could also have been tested and compared in the same way.

Figure 5 shows the Level 3 model and maximum temperature scanning track results with island scan from right to left, chosen for further study at Level 4.

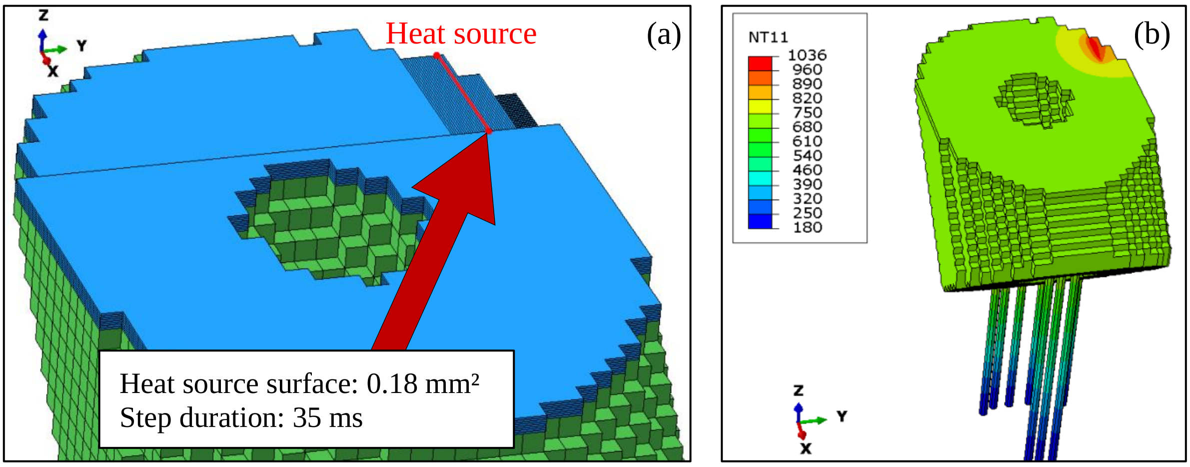

Figure 5: Level 3 model with (a) a particular scan track heat source, and (b) maximum temperature results from right to left

2.7 Level 4 description

Like the other levels, Level 4 is a zoom of the Level 3 identified region where a too high or too low temperature is attained. Level 4 models an island's particular scan track.

At this level, only small portions of the scan track are heated one by one, as fragments of the previous lineic heat source along the direction of the laser beam's displacement. This way, it is possible to identify whether the region with the highest temperature rise is at the beginning, the middle, or the end of the scan track. It is also possible to define the impact of a scanning direction (back and forth or one direction) at this level, or to analyze contouring strategies. A given scan track portion can be retained for further analysis at Level 5.

2.8 Level 4 results

At Level 4, the direction of the scan track is investigated. From Level 3, a particular scan track was identified, but at Level 4, a comparison regarding the scan track direction could be done.

Hence, compared to Level 3, the geometrical domain was again reduced, and both the meshes and time increments were refined.

At this level, small surface heat fluxes were applied upon the upper surface of the model (see Figure 6), these loadings simulate portions of the scan tracks at scanning speed. Averaging the laser beam's impact at this level allows to reduce the computational time (since the beam size is much smaller) but provides an overview of its impact on the track's different locations (at the beginning, the midway, or the end of it), as well as its direction.

Hence, at this level, the most suitable scanning direction can be found regarding the temperature’s impact. We are also able to identify the portion in which the temperature would elevate the most.

Both the model and the results of Level 4 are displayed in Figure 6. The particular track portion shown is the one with the higher temperatures and is considered in Level 5.

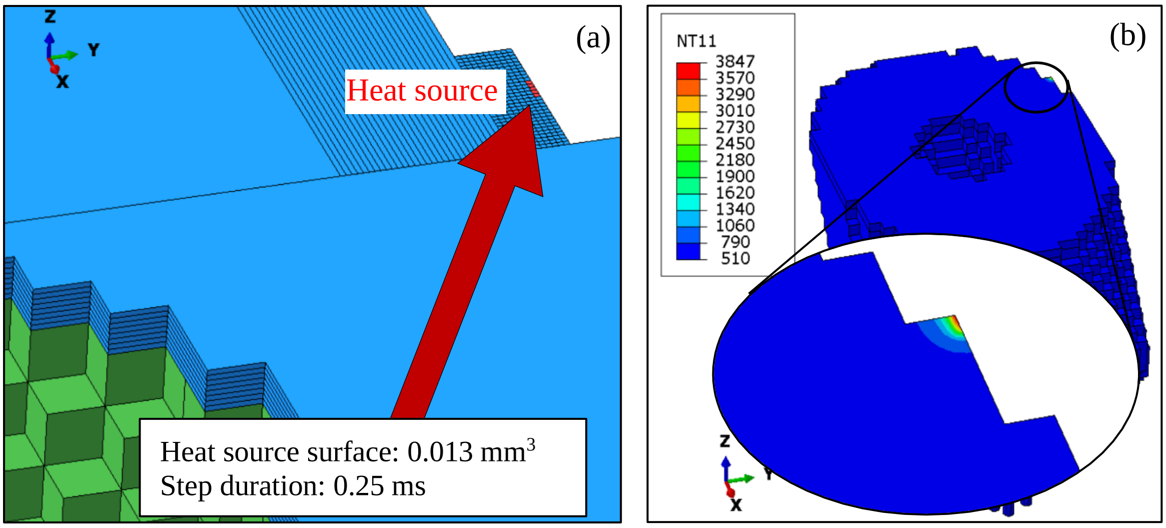

Figure 6: Level 4 model with (a) a particular scan track portion heat source and, (b) maximum temperature results from top to bottom direction

2.9 Level 5 description

Level 5 is a zoom of the Level 4 scan track portion and meets the melt pool's size where heat is applied as a surface heat flux with a gaussian profile and where all melting physics should be included. We have not developed this model, already largely studied in the literature.

At Level 5, it would be possible to simulate the precise fluid dynamics, convection heat transfer within the liquid, and other microscale phenomena while using the initial and boundary conditions computed at previous levels. In the scope of this study, Level 5 is performed using solid homogeneous continuous FE analysis, but more precise simulation methods could be used.

2.10 Level 5 results

Level 5 is the last level of this multiscale approach. While it consists theoretically of a microscale model, it still considers the bodies as homogeneous continuum solids and the conduction in solids as the major heat transfer mechanism. Improvements would of course consist of modeling Level 5 with the thermal-fluid flow or thermal-fluid-vaporization models, which would be much more precise in capturing key physical factors at this scale [9], but these are outside the scope of the present work. Also, it is obvious that the part boundary should be refined at this level, but this do not change the spirit of our method.

A melt pool's size flux heat source is applied at the top of the upper layer at this level (see Figure 7). It is used to simulate the path of the laser beam as a punctual heat source application.

Compared to Level 4, the geometrical domain is reduced, and both the time steps and the meshes are refined.

Figure 7 shows both the Level 5 model, with a melt pool-like loading, and the results at the time of the maximum temperature.

This Level 5 model could be used practically in adapting laser power at the beginning or the end particular scan tracks for instance, and could be used to study most phenomena considered in the literature such as the melt pool denudation, spatters, keyholes, etc.

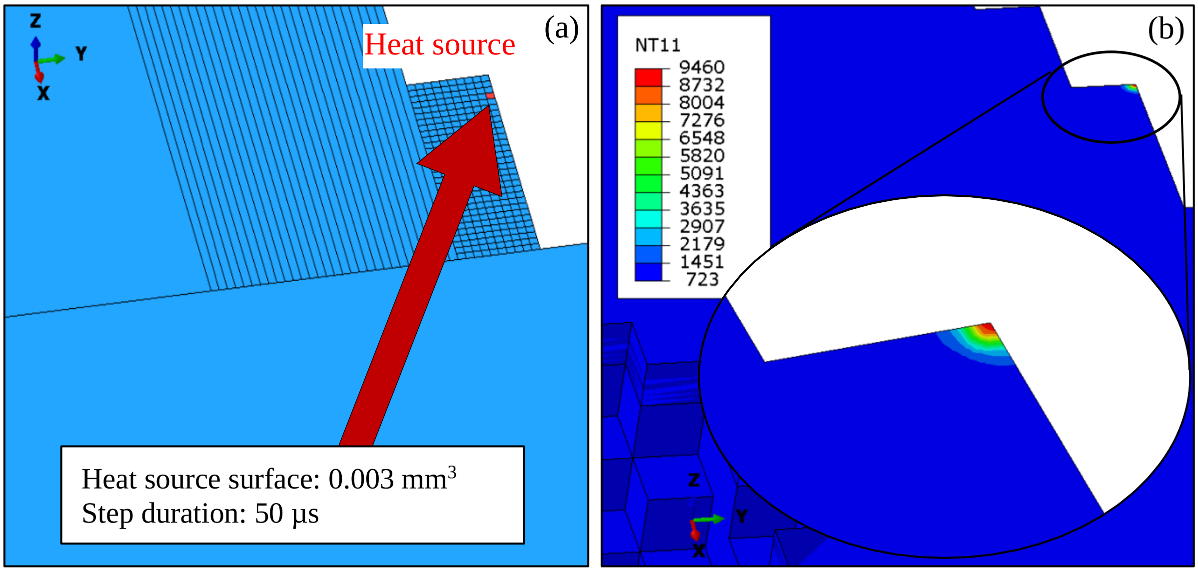

Figure 7: Level 5 model with (a) a particular melt pool-like heat source, and (b) maximum temperature results

3 CONCLUSIONS

A novel multiscale thermal simulation approach has been presented, and a demonstrative study case on an industrial part was performed. While using a standard commercial FE package, this approach enables the user to perform a fine thermal finite element simulation in reduced computational times.

Five distinct temporal and spatial scales are developed, from macroscale to microscale, to zoom in to zones with extreme (maximum and minimum) temperatures. Level 1 uses macrolayers and volumetric heat sources to model the whole build plate considering all the parts and supports. Level 2 is zoom in to specific layers, where the scanning pattern (stripe or chessboard for instance) is studied. Level 3 uses lineic heat sources to model the whole scan tracks and determine the best scan track directions among the chosen configurations. Level 4 zooms in to scan track portions in order to determine the temperature fields at the beginning, the end and the middle of the selected scan tracks. Level 5 is similar to the melt pool models developed in the literature and could be used to study complex microscale phenomena.

The geometrical domains are gradually decreased with the zooms between the levels. The injected energy and the times used within each step correspond to those of the actual manufacturing process.

The zoom assumptions of the multiscale approach mainly rely on the assumption that the machine manufacturer's laser parameters yield parts with high densities (above 99%), and regions with porosities are suffering a significant temperature rise.

The temperature fields computed at each level are used to identify regions for the next level and may be used to predict porosity location within the parts. A correlation between thermal results and porosity locations will be studied shortly.

This model's precision and computational time will also be optimized using specific thermal assumptions.

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