Development of a simulation approach for laser powder bed fusion based on scanning strategy selection

Panagis Foteinopoulos¹ · Alexios Papacharalampopoulos¹ · Konstantinos Angelopoulos¹ · Panagiotis Stavropoulos¹

Received: 24 November 2019 / Accepted: 4 June 2020 / Published online: 16 June 2020
© The Author(s) 2020

Abstract

An important quality-related aspect of metal-based additive manufacturing (AM) parts is the existence of thermal stresses and deformations. To address this issue, a 3D thermal simulation approach for powder bed fusion (PBF) processes has been developed, along with the definition of an index that encapsulates the intensity of the non-uniformity of the thermal field. The proposed approach delivers sufficient and computationally low-cost results regarding the intensity of the expected thermal stresses and deformations. A case study of eighteen parts is presented, in which eight different scanning strategies are tested to identify the optimum scanning strategy in terms of thermal stresses and deformations. Finally, the impact of different design elements on the importance of the scanning strategy selection in terms of thermal stresses and deformations is discussed. Both the developed model and the index have been benchmarked using experimental and computational data.

Keywords Additive manufacturing · Thermal modeling · Scanning strategy · Infill patterns · Thermal stresses · Thermal deformations

1 Introduction

Additive manufacturing (AM) is a very promising manufacturing technology with several advantages, the most important of which being the manufacturing freedom it offers [1]. This freedom makes part complexity almost cost-free [2], a fact that has a direct impact on several industrial sectors [3] and on part design [4], as well. Moreover, AM renders the production of small batch sizes viable in terms of cost, thus paving the way for the mass customization of products [5]. The abovementioned advantages combined with the extensive industrial application of metal AM have led to a steadily increasing interest for laser powder bed fusion (LPBF) [6], which is one of the most popular metal AM process groups. The majority of the metal AM processes utilize a thermal-process mechanism for the joining of new layers [2]. However, in LPBF, dynamic temperature-profile changes occur [7]. This leads to mechanical and geometrical deviations in

the final parts [8], as well as cracking (Fig. 1, left image), which are attributed to the extreme temperature variations [11]. These constitute some of the most important quality issues [3] that occur in LPBF and other metal-based AM applications [12].

Such variations are not only caused by the intensity of the laser power but also by the scanning strategy [13] because it defines the heating sequence and path. Consequently, the scanning strategy directly affects the development of thermal stresses and deformations; as a result, the dimensional accuracy and the mechanical properties of the final parts are affected as well [14, 15]. Therefore, the optimization of the scanning strategy is highly important [16].

Typically, AM slicing software offers predefined scanning strategy/infill patterns from which the user can select [17–20]. This selection can be based on a set of criteria (Fig. 2); a widely used criterion is the minimization of the anisotropy effects [21–26]. Another criterion is to reduce the build time and cost [27–30]. To select the best scanning strategy, custom infill optimization algorithms have been developed, aiming to the minimization of the start/stops of the scanner head on the same layer [31]. Specific design considerations may also be used as criteria [32], such as the optimization of the internal topology regarding static and rotational stability [33]. Certain studies have focused on correlating the scanning strategy

✉ Panagiotis Stavropoulos
pstavr@lms.mech.upatras.gr

¹ Department of Mechanical Engineering and Aeronautics, Laboratory for Manufacturing Systems and Automation, University of Patras, Patras, Greece

Fig. 1 Failed parts due to thermal stresses in metal AM (left image [9], right image [10])

selection with dimensional accuracy. In [34], it has been stated that accurate manufacturing can be achieved by using a scanning strategy that follows the contour geometry, such as boundary contours [34] or various contour-map patterns [35, 36].

However, in thermal-based AM, such as metal AM applications, the scanning strategy selection is highly important because it impacts the resulting thermal field [13], which, in turn, directly affects the intensity of the developed thermal stresses and deformations: high temperature gradients lead to increased thermal stresses and deformations [7, 15]. This is one of the major quality issues in metal AM applications. However, the minimization of thermal stresses and deformations are not commonly considered as a criterion for the selection of the scanning strategy (Fig. 2) because of the high computational cost and the very long simulation time that is required for the evaluation of different alternatives. It should be noted that the thermo-mechanical phenomena that take place in metal AM processes are highly dynamic in time and space [37]; thus, their simulation is costly in terms of computational time and memory [7].

Consequently, in most studies, either very short manufacturing times or very small parts are simulated [38–43]. Even AM-dedicated commercial simulation packages face the issues of high computational cost and demanding time requirements for such simulations [44]. However, it should be noted that when different scanning strategies are used, the simulation of the entire progression of the process considering the exact movement of the scanner head in the

entire volume of the part is crucial for the correct estimation of the expected thermal stresses/deformations. The standard practice for the comparison of the expected thermal stresses and deformations is to perform a thermal-mechanical analysis, which is even more computationally intense than a thermal one, and then to evaluate the results by comparing the resulting deformations (Fig. 3). To address the aforementioned issue, a 3D thermal simulation will be presented in this study. In the proposed simulation, the process parameters (PPs) and scanning strategy are selected using the thermal field instead of the thermal-induced thermal stresses and deformations. In this manner, the calculations are significantly faster. To achieve this, a stress formation tendency index (SFTI) was developed that encapsulates the intensity of the non-uniformity of the thermal field, which causes the development of thermal stresses and deformations [15] (Fig. 3).

Consequently, by calculating the thermal history and by utilizing the SFTI, the evaluation of different alternatives becomes possible without the need to perform a coupled mechanical analysis. Therefore, in terms of computational time, this approach enables the practical application of the criterion of the minimization of thermal stresses and deformations for the scanning strategy selection. This will lead in parts of higher dimensional accuracy, better mechanical properties, and improved quality (Fig. 4).

It should be noted that the proposed method was not developed to substitute the existing criteria for scanning strategy selection, but to be used in addition to them. More specifically, the selected scanning strategies that satisfy the criteria of

Fig. 2 Different criteria for the selection of the scanning strategy for a part and the added value of the present work (orange dotted arrow)

Fig. 3 Proposed approach: enables the significantly faster and practical comparisons of PPs and scanning strategy selections

the resulting anisotropy and specific geometrical considerations for a given part can be tested using the proposed approach. In this manner, an indication can be obtained of the expected thermal stresses and deformations for each of the selected scanning strategies. The proposed method should be used as an additional criterion to the already existing, thus leading to parts of better quality. Its main aim is to increase the efficiency of simulations in the evaluation of scanning strategy alternatives concerning the intensity of the resulting thermal strategies and deformations.

2 Approach

To improve the quality of parts manufactured via LPBF, the proposed model simulates the entire thermal history of the manufacturing process in order to support the selection of the values of the PPs and the scanning strategy that will minimize the thermal stresses and deformations. The thermal model considers the exact movement of the scanner head (a gantry scanner head will be assumed hereafter), leading to an accurate representation of the scanning strategy and its effects on the resulting thermal field. Moreover, the addition of new layers is simulated, the different material properties of powder and solidified material are considered, and the material properties are functions of temperature. The only input required is the build-file (G-Code) of the part, from which the PP selections and movement sequence of the scanner head are imported to the model. After the simulation of the thermal history has been completed, the value of the index encapsulating the non-uniformity of the thermal field is calculated.

Fig. 4 Benefits of the proposed approach

The simulation approach has been adjusted for the LPBF AM process group for metal-based AM applications. Figure 5 illustrates a schematic of the proposed simulation approach.

2.1 G-Code reader module

The first step of the simulation approach is the reading of the inputs from the build-file (G-Code) of the part. The process parameters are imported and the movement sequence of the scanning head is then represented as a set of 2D arrays, one for each layer of the part. More specifically, each array represents the area of one layer; to map the path of the scanner head over the layer, the cells of the array are filled with numbers corresponding to the order in which the scanner head passes over them. In this manner, a set of arrays is created that encapsulates the movement sequence of the laser beam spot. This allows for the simulation of support structures as well. The module of this procedure is schematically presented in Fig. 6.

2.2 3D thermal model

The proposed model is an extension of the validated work of the authors presented in [37, 45]. The following assumptions have been made:

- The proposed model concentrates on the metal-based LPBF AM process. Metals are heat conductors; as a result, heat transfer through radiation is negligible compared to that through conduction [37, 46]. Therefore, heat transfer through radiation has not been considered.

Fig. 5 Schematic of the 3D thermal simulation approach

- The building platform of the machine was considered as a heat sink; therefore, its temperature was maintained constant [37].
- Evaporation has not been taken into account for the sake of simplicity and in order to maintain computational costs at a minimum [39, 47].

It should be noted that the considered level of detail appeared to be adequate for the evaluation of different scanning strategies using the SFTI in the benchmarking section.

Each time a layer is added, the part is discretized into a number of nodes, which are then divided into different groups. Figure 7 a illustrates a qualitative representation of the 3D node-mesh using the following color scheme for the different types of nodes: side nodes (blue, yellow, magenta, cyan), top

nodes (red), bottom nodes (green), and internal nodes (black). A qualitative presentation of a 2D section of the 3D node-mesh can be seen in Fig. 7b, which illustrates the different phenomena that take place and the respective boundary conditions that have been used.

Because a gantry scanner head was assumed for this study, a Gaussian profile can be assumed for the laser beam intensity, which is described as a function of distance from the laser beam axis [37]. This condition was applied to the heated nodes of the top layer. Thermal losses from the top side of the part to the environment due to convection were modeled using a Neumann boundary condition. The same boundary condition was used for the side nodes (blue, yellow, magenta, and cyan nodes in Fig. 7a) because thermal losses to the environment (air) due to convection take place there as

Fig. 6 Detailed schematic of the G-Code reader module of the presented simulation approach

Fig. 7 **a** 3D qualitative depiction of the node types. **b** 2D section illustrating the phenomena that take place and the boundary conditions used

well [37]. Considering the machine platform as a heat sink of a constant temperature, the thermal losses of the bottom layer (green nodes in Fig. 7) have been modeled using the convection equation. However, a modified heat transfer coefficient of higher value was used in order to describe the higher rate of energy exchange that takes place between the part and the

machine platform [37]. More details on the boundary conditions can be found in [37].

The phenomenon of conduction was expected to take place in the internal nodes (black nodes in Fig. 7a, b). The differential equation of heat conduction through an isotropic material in 3D Cartesian coordinates was used:

$$\nabla^2 T = \frac{k}{c_p} \frac{\partial T}{\partial t}, \quad (1)$$

where T is the nodal temperature, c_p is the specific heat capacity, and k is the thermal conductivity of the material.

To maintain a low computational cost, a node-distancing algorithm was used in conjunction with layer addition. More specifically, the addition of a number of layers is simulated by adding layers of nodes on top of the existing ones. After the maximum number of layers of nodes has been reached, the addition of the remaining material layers is simulated utilizing an adaptive meshing algorithm: the distance between the nodes of the lower part of the mesh is increased; the total increase corresponds to the thickness of one layer. A schematic of the adaptive meshing algorithm can be seen in Fig. 8, in which it can be observed that the same number of nodes is used to describe both N and $N+1$ number of layers. In this manner, the computational cost is maintained constant. Thus, the computational requirements are kept to a minimum, whereas the accuracy is maintained [37] because the heat transfer phenomena that take place at the lower part of the z -axis are far less dynamic than those taking place at the upper part of the z -axis. The temperature values of the nodes at their new positions are calculated using a spline interpolation. The increased distances between the nodes have been considered in the convergence of the simulation.

Owing to the use of the adaptive meshing algorithm, the distances between the adjacent nodes at the lower part of the z -axis are not the same on each side. Therefore, the discretized form of the central finite difference (FD) equation has been acquired using the Taylor theorem and it was implemented for

the discretization of Eq. (1). The stencil equation for an internal node is

$$\begin{aligned} & \left(T_{m+1,n,o}^{t+1} + T_{m-1,n,o}^{t+1} \right) \frac{a}{\Delta x^2} + \left(T_{m,n+1,o}^{t+1} + T_{m,n-1,o}^{t+1} \right) \frac{a}{\Delta y^2} \\ & + T_{m,n,o+1}^{t+1} \left(\frac{a}{\Delta z_1^2} - \frac{a}{\Delta z_1(\Delta z_1 + \Delta z_2)} + \frac{a}{\Delta z_2(\Delta z_1 + \Delta z_2)} \right) \\ & + T_{m,n,o-1}^{t+1} \left(\frac{a}{\Delta z_2^2} + \frac{a}{\Delta z_1(\Delta z_1 + \Delta z_2)} - \frac{a}{\Delta z_2(\Delta z_1 + \Delta z_2)} \right) \\ & + T_{m,n,o}^{t+1} \left(-\frac{2a}{\Delta x^2} - \frac{2a}{\Delta y^2} - \frac{a}{\Delta z_1} - \frac{a}{\Delta z_2} \right) \\ & = \frac{T_{m,n,o}^{t+1} - T_{m,n,o}^t}{\Delta t}, \end{aligned} \quad (2)$$

where m is the number of the node along the x -axis, n along the y -axis, o along the z -axis, and a is the thermal diffusivity of the material.

The convergence of the numerical scheme is ensured by following a procedure similar to that of [37]. The heating of the same set of nodes for multiple time steps ensures the numerical stability and the accuracy of the results. The next set of heated nodes is identified from the array corresponding to this layer. This procedure is repeated until the exact movement of the scanner head over the current layer is simulated. After the completion of a layer, a check is performed of whether the part is finished. The next layer follows until the entire manufacturing procedure is simulated.

To include the energy required for the melting/solidification phase change, the method of the apparent heat capacity was used [37, 48]. Different material properties,

Fig. 8 Schematic of the adaptive meshing algorithm (2D section)

namely, the thermal conductivity, specific heat, and density, were used for the powder and they were calculated using the Maxwell model [37, 49]. The material properties of the porous medium were initially used for all the nodes that were being added to intermediate steps of the simulation. Next, a temperature check is performed; if the temperature of a node exceeds the melting temperature of the material, the material properties that correspond to a dense, non-porous material are used for this node for the remaining simulation.

2.3 Stress formation tendency index

In thermo-mechanical problems, the temperature gradient causes displacements, which translate to thermal stresses and deformations in parts [14, 15]. This is expressed via the generalized Navier equation:

$$\mu \nabla^2 \mathbf{u} + (\lambda + \mu) \nabla (\nabla \cdot \mathbf{u}) + b \nabla T = \rho \ddot{\mathbf{u}}, \quad (3)$$

$$\lambda = \frac{E \nu}{(1 + \nu)(1 - 2\nu)} \quad (4)$$

$$b = \frac{\alpha_v E}{1 - 2\nu} \quad (5)$$

where μ is the shear modulus, $\mathbf{u}$ is the displacement vector, λ is Lamé's first parameter, T is the temperature, ρ is the material density, E is the Young's modulus of the material, ν is the Poisson's ratio of the material, and α_v is the volumetric coefficient of thermal expansion of the material.

An index based on the gradient of the temperature was defined because it causes thermal stresses and deformations [7, 15]. The index encapsulates the intensity of the tendency for the creation of thermal stresses and deformations. Therefore, it will henceforth be referred to as the Stress Formation Tendency Index (SFTI). The mean value of the gradient in the xy -plane of the nodes of the upper region of the part (static mesh) is calculated according to the following:

$$\text{SFTI} = \varepsilon_{\text{Number of layers}} \left\{ \frac{\sum_{\text{every node of layer}} |\nabla_{xy} T|}{N_L} \right\}, \quad (6)$$

where N_L is the number of nodes belonging to the layers of nodes that form a real part layer. The scanning strategies determine the heating sequence on the xy -plane; therefore, to compare the scanning strategies to one another, the gradient of the xy -plane is preferred over the xyz one. Moreover, the main purpose of this index is to support the selection of the scanning pattern, which is reflected in the xy -plane gradient, rather than to support the selection of the starting scanning point of each layer, which is reflected in the z direction gradient. Therefore, the xy -plane gradient was preferred to more clearly represent the effect of the scanning pattern selection. To calculate Eq. (6), a central FD scheme was used for its discretization.

The greater the gradient of the temperature in the xy -plane is, the more intense the non-uniformity of the thermal field on that plane is. Consequently, the use of the SFTI enables the evaluation of alternatives regarding the selection of the PPs and the scanning strategy: the lower the value of the SFTI is, the more minimized the thermal stresses and deformations in the part are expected to be. The ability of the SFTI to predict the intensity of the thermal stresses and deformations will be validated in Sect. 3.

To reduce numerical complexity, the material properties of only two phases were used in the model: unsolidified powder and solidified material. The effect of the molten phase on the stresses was not considered, which proved to be in quite good agreement with reality for the following reasons. At any given time, the material in the liquid phase (i) remains in the liquid phase for a very short time, (ii) has a very small volume, (iii) it can be considered to be a solid with a Poisson's ratio of 0.5, and (iii) the z component of the stresses have not been considered in the SFTI (only the xy -plane gradient is used for the SFTI calculation). It should be noted that the considered level of detail appeared to be adequate for the evaluation of different scanning strategies using the SFTI in the benchmarking section.

3 Validation of the stress formation tendency index

The ability of the presented SFTI to predict the intensity of the thermal stresses and deformations will be validated in the present section. The thermal analysis and the calculation of the corresponding SFTI for each of the scanning strategies presented in Fig. 10 have been performed using the developed model. Moreover, a transient thermomechanical analysis for each of the scanning strategies was performed using a licensed and validated [50] commercial software [51]. Steel powder bed material was assumed. A small part and a limited timespan were used (Table 1) owing to the computational requirements of the thermomechanical analysis. The different scanning strategies used in this benchmarking test can be seen in Fig. 9.

Table 1 Part dimensions and important PPs

Property	Value
Part dimensions	$3 \times 3 \times 0.5$ mm
Spot size	0.5 mm
Scan speed	50 mm/s
Total process time	0.36 s
Power	250 W
Absorptivity	0.4

Fig. 9 Scanning strategies used for the benchmarking

The scope of these simulations was to validate the ability of the presented SFTI of identifying which scanning strategy will lead to higher thermal stresses and deformations. Therefore, for the sake of simplicity, no overlap has been assumed. The results of the analyses are summarized in Table 2 and are graphically presented in Fig. 10. It may be observed that the use of different scanning strategies directly affects the intensity of the developed thermal stresses and deformations. Moreover, it may be seen that the thermal stresses and deformations are the most prominent for the first scanning strategy, followed by those of the second, and finally, by those of the third.

In Fig. 11, it may be observed that the SFTI of the first scanning strategy is the highest, followed by that of the second scanning strategy, and finally, by that of the third. The SFTI results are in good agreement with those obtained from commercial software (Fig. 10). Therefore, the SFTI succeeded in correctly determining the magnitude of the effects of the scanning strategies on the thermal stresses and deformations.

Consequently, the developed index allows the evaluation of alternatives regarding the prediction of the intensity of the expected thermal stresses and deformations when different scanning strategies are used.

Moreover, it should be pointed out that using the same computer system, the numerically optimized simulation approach required only 6 s for each analysis, whereas the mean time required for the thermomechanical analyses was 0.73 days (Fig. 12).

4 Case study

The first aim of this case study is to demonstrate the ability of the proposed simulation approach and of the SFTI to evaluate different alternatives in terms of the effect of a scanning strategy on the value of the SFTI. The second aim is to investigate different part design characteristics on the importance of the scanning strategy selection in terms of the SFTI value.

A set of parts with different designs were used in the case study; the parts were divided in five groups. Each group consisted of parts that shared common design elements. In Group 1, the value of $\frac{xy\text{-plane area}}{\text{Largest } xy \text{ dimension}}$ decreased from part one to part four. All parts of Group 2 had the same dimensions in the x , y , and z , featuring a circular hole of increasing diameter at the center of the xy -plane. Group 3 shared the same characteristics with Group 2, with the difference that the shape of the hole was rectangular instead of circular. There was a correspondence between the parts of Group 2 and three in terms of the $\frac{\text{Area}}{\text{Empty Space Area}}$, as listed in Table 3. The thickness of the parts of Group 4 was constant and their xy -plane surface was square, with an increasing area. Finally, the parts of Group 5 had the same xy -plane area with an increasing thickness. Certain parts belonged to more than one group. More details on the parts and their dimensions are available in Fig. 13 and Table 3.

The aforementioned part designs were selected to investigate the importance of the scanning strategy selection for geometrical shapes that are building blocks for more complex

Table 2 Analyses results according to commercial software

Deformations	Scanning Str. 1	Scanning Str. 2	Scanning Str. 3
Mean deformation (m)	1.59E-05	1.54E-05	1.44E-05
Standard deviation (m)	3.43E-06	2.77E-06	2.31E-06
Max. (m)	2.47E-05	2.13E-05	1.89E-05
Stresses			
Mean stress (Pa)	1.03E+10	1.04E+10	9.66E+09
Standard deviation (Pa)	2.09E+09	2E+09	1.61E+09
Max. (Pa)	1.38E+10	1.27E+10	1.12E+10

Fig. 10 Mean thermal stresses and deformations results

parts. Hence, this case study also serves in increasing the intuition of the reader on the impact of different building blocks on the importance of the scanning strategy selection in the magnitude of thermal stresses and deformations.

The build-file (G-code) for each part was created using each of the different scanning strategies in Fig. 14. Eight different scanning strategies were selected; these comprised the most commonly used ones, as well as unique and different strategies of path planning.

A set of analyses was then performed on each of the part designs using all the aforementioned scanning strategies and the SFTI value was calculated for each strategy.

5 Results and discussion

Figure 15 illustrates the SFTI values of the different scanning strategies of Fig. 14 for the parts of Group 1. The values have been normalized for each part to facilitate comparison. The standard normalization method was implemented: the SFTI values of each part were divided by the lowest SFTI value that corresponded to that specific part. It may be observed that

there are significant differences between the SFTI values when different scanning strategies are used. More specifically, scanning strategies 4, 5, and 6 should be avoided for Part 1, because their corresponding SFTI values are the highest. Moreover, scanning strategies 1, 2, and 8 should not be preferred at all, if possible, whereas the most preferable ones are 3 and 7. Regarding Part 2, scanning strategies 3 and 6 should be avoided. In addition, scanning strategies 4, 7, 8, and 5 should not be preferred at all, whereas the most suitable ones are 2 and 1. In Part 3, scanning strategies 4, 6, 5, 8, 1, and 7 should be avoided; the most preferable ones are 3 and 2. Finally, in Part 4, scanning strategies 4, 5, and 6 should not be employed at all, if possible, whereas 3, 2, and 7 should be preferred.

It may be observed that there are important differences between the SFTI values of Part 1 when different scanning strategies are used. The difference between the SFTI values of Part 2 is smaller and becomes even smaller in parts 3 and 4. This can also be confirmed by calculating the standard deviation of the SFTI values for each part, which is 30.66 for Part 1, 26.52 for Part 2, 15.02 for Part 3, and 10.05 for Part 4, as can be seen in Fig. 16 (using the original values, not the normalized ones). This is attributed to the fact that the scanning strategy selection affects the intensity of the resulting thermal gradients with varying importance in parts with different design elements. High values of standard deviation mean that

Fig. 11 SFTI results for the different scanning strategies **Fig. 12** Mean time required for the analyses (logarithmic scale)

Table 3 Dimensions of parts used for simulations

Group 1	Part 1	Part 2	Part 3	Part 4
Dimensions (mm)	$15 \times 15 \times 3$	Diameter: 15 mm Thickness: 3 mm	$15 \times 5 \times 3$	$20 \times 3 \times 3$
$\frac{xy\text{-Plane Area}}{\text{Largest } xy \text{ dimension}}$ (mm)	15	11.78	5	3
Group 2	Part 5	Part 6	Part 7	Part 8
Dimensions (mm)	$15 \times 15 \times 3$	$15 \times 15 \times 3$	$15 \times 15 \times 3$	$15 \times 15 \times 3$
Hole Diameter (mm)	3.5	6.77	10	11.3
$\frac{\text{Area}}{\text{Empty Space Area}}$	23.40	6.25	2.87	2.24
Group 3	Part 9	Part 10	Part 11	Part 12
Dimensions (mm)	$15 \times 15 \times 3$	$15 \times 15 \times 3$	$15 \times 15 \times 3$	$15 \times 15 \times 3$
Hole dimensions (mm)	3.1×3.1	6×6	8.85×8.85	10×10
$\frac{\text{Area}}{\text{Empty Space Area}}$	23.41	6.25	2.87	2.25
Group 4	Part 13	Part 1	Part 14	Part 15
Dimensions (mm)	$10 \times 10 \times 3$	$15 \times 15 \times 3$	$20 \times 20 \times 3$	$25 \times 25 \times 3$
xy-plane area (mm ²)	100	225	400	625
Group 5	Part 13	Part 16	Part 17	Part 18
Dimensions	$10 \times 10 \times 3$	$10 \times 10 \times 5$	$10 \times 10 \times 7$	$10 \times 10 \times 9$

there is a considerable difference between the STFI results for different scanning strategies for a specific part. Therefore, the selection of the scanning strategy for that part would be more important than when the value of the standard deviation between the STFI results for different scanning strategies is high. To correlate the importance of this decision with different part design characteristics, the standard deviation between the SFTI values of the parts of each part group (Fig. 13) for all

scanning strategies (Fig. 14) was calculated and can be seen in Fig. 16. This depiction of the results is more concise, allowing for an easier evaluation of the effect of the different design characteristics on the importance of the scanning strategy selection. Next, the results of the different part groups based on Fig. 16 will be discussed. The SFTI results of the remaining part groups depicted in the manner of Fig. 15 can be found in the [Appendix](#).

Fig. 13 Parts and part groups used for simulations

Fig. 14 Different scanning strategies (infill patterns) used for the presented simulations

Group 1 It may be observed that the higher the value of $\frac{xy\text{-plane area}}{\text{Largest } xy \text{ dimension}}$ is, the more important the selection of the scanning strategy is in terms of the developed thermal gradients. This can be attributed to the fact that the existence of surfaces with uniform xy dimensions does not restrict the path planning options of different scanning strategies. On the contrary, great differences between the x and y dimensions—and therefore, long and narrow xy -plane surfaces—restrict the path planning options of different scanning strategies. Thus, paths of increasing similarity and similar thermal gradients occur.

Group 2 The importance of the scanning strategy selection increases as the hole diameter increases. The maximum importance is reached for the second part of the group (part 6). However, as the hole diameter increases, a threshold is reached; therefore, the importance of the selection becomes less for the third and fourth part of the group (Parts 7 and 8). This is attributed to the limited available area that does not allow many options for the movement of the scanner head.

Group 3 The importance of the scanning strategy selection increases as the area of the hole increases for the first three parts of the group (Parts 9, 10, and 11). This can be associated with the fact that as the hole area increases, it becomes a more dominant design characteristic of the part. Thus, certain scanning strategy selections lead to a more uniform distribution of temperature owing to the manner in which their path-planning algorithm interacts with the rectangular hole. However, after a threshold of the hole area has been reached, the selection significance decreases. This can be observed for the fourth part of the group (Part 12), and it is attributed to the limited available part area.

Group 4 All parts of the group feature a square surface of increasing area in the xy -plane, while their thickness is maintained constant. It may be observed that the standard deviation of the STFI values decreases as the area of the surface becomes larger. This can be attributed to the fact that as the xy -area increases, the greater becomes the similarity with the contact surface to the AM build platform, which has a lower

Fig. 15 Normalized STFI results for parts of Group 1, for the different scanning strategies of Fig. 14

Fig. 16 Standard deviation of the SFTI values of each part

temperature. Therefore, the thermal losses are also higher and the intensity of the thermal gradients is smoothened out.

Group 5 It may be observed that the importance of the scanning strategy selection slightly decreases. This is ascribed to the fact that parts of greater thickness—and therefore, mass—tend to smoothen out the intensity of the thermal gradients of the upper layers owing to their higher temperature than that of the build platform.

It should be pointed out that certain phenomena have opposing effects. More specifically, in Group 1, although the contact surface to the machine platform decreases from Part 1 to Part 4, the uniformity of the xy dimensions decreases. Therefore, two phenomena with opposing effects take place: the increase in the contact surface, which leads to a lower SD value, and the uniformity of the xy surface area, which leads to a higher SD value. In Group 1, it may be observed that the uniformity of the xy surface area is the most dominant phenomenon because the SD values decrease from Part 1 to Part 4.

6 Conclusions

In this study, a 3D thermal simulation approach has been presented, which allows significantly more practical simulations in terms of the required computational cost. It enables a considerable faster evaluation of alternatives in computation thermal analysis compared with that of thermomechanical models. This fast evaluation was achieved via the use of the Stress Formation Tendency Index (SFTI) that encapsulates the non-uniformity of the thermal field, which causes thermal stresses and deformations to develop. The ability of the SFTI to encapsulate the resulting thermal stresses and

deformations was validated through thermomechanical simulations.

It was found that the scanning strategy selection affects the resulting thermal field and thermal gradients and, consequently, the intensity of the developed thermal stresses and deformations. Utilizing the developed 3D thermal simulation approach and the SFTI, the application of an additional criterion for scanning strategy selection is practically possible in terms of computational resources: the minimization of thermal stresses and deformations to increase part quality.

In terms of its impact on thermal gradients, the importance of the scanning strategy selection varies and depends on part design elements. More specifically, the selection of the scanning strategy is of higher importance for parts with a surface of uniform xy dimensions than for parts featuring long and narrow xy -plane surfaces. In addition, the existence of holes of increasing diameter increases the importance of the scanning strategy selection. However, after a diameter threshold has been reached, the importance of which scanning strategy would be selected greatly decreased. In addition, it is of higher importance when rectangular holes are featured instead of cylindrical ones. Moreover, the significance of the selection decreases for parts of low thickness featuring large xy -surfaces, whereas it slightly decreases as the part thickness increases. Finally, it should be taken into account that there are phenomena that lead to opposing effects. More specifically, an increase in the xy area would normally lead to a lower SD value. However, if the increase in the area occurs in a manner that leads to a more uniform xy surface, the SD value may increase because these aforementioned phenomena are opposed to one another, and the dominance of one over the other depends on various material and process parameters.

Regarding future work, a newer version of the proposed 3D thermal simulation approach could be developed, which would be adapted to direct metal deposition. This could be

achieved by adding the solidified material at each time step instead of the entire layer in powder form. Furthermore, boundary conditions can be adjusted to ensure that convection is implemented as boundary condition at all outer surfaces. In addition, further application of the proposed method and new case studies need to be investigated using parts with a more complex geometry. Subsequently, simulation results should be compared with experimental data.

Moreover, the creation of a path planning optimizer capable of developing customized path planning strategies for any given part would be desirable. Towards this, the presented 3D thermal simulation approach can be utilized for the minimization of the STFI value; consequently, thermal stresses and deformation would be minimized as well.

Funding information This work is under the framework of EU Project FreeWheel. This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 768908.

Appendix

The SFTI results of the remaining part groups (Fig. 13) of the case study are presented here. In Fig. 17, the results of the second part group can be seen. It may be observed that as the diameter of the hole increases, the most preferable scanning strategy changes from 7 to 5. In a similar manner, the scanning strategies that should be avoided change from 4 and 6 to 2 and 3. However, the difference between the SFTI values has decreased in Part 8, which signifies the decreased importance of the scanning strategy selection for parts featuring a small xy -area. Figures 18, 19, and 20 illustrate the results of groups 3, 4, and 5, respectively. By observing the SFTI values for each scanning strategy and each part, the most preferable scanning strategies can be identified, as well as those that should be avoided. The correlation of the suitability of the different scanning strategies with the design elements of each part group can be found in Sect. 5, in the discussion of Fig. 16.

Fig. 17 Normalized STFI results for parts of Group 2, for the different scanning strategies of Fig. 14

Fig. 18 Normalized STFI results for parts of Group 3, for the different scanning strategies of Fig. 14

Fig. 19 Normalized STFI results for parts of Group 4, for the different scanning strategies of Fig. 14

Fig. 20 Normalized STFI results for parts of Group 5, for the different scanning strategies of Fig. 14

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Stavropoulos P, Foteinopoulos P (2018) Modelling of additive manufacturing processes: a review and classification. *Manuf Rev* 5:7–33. <https://doi.org/10.1051/mfreview/2017014>
2. Bikas H, Stavropoulos P, Chrysosolouris G (2016) Additive manufacturing methods and modelling approaches: a critical review. *Int J Adv Manuf Technol* 83(1–4):389–405. <https://doi.org/10.1007/s00170-015-7576-2>
3. Chrysosolouris G (2006) *Manufacturing systems: theory and practice*, 2nd edn. Springer Science & Business Media, New York
4. Adam GA, Zimmer D (2014) Design for additive manufacturing—element transitions and aggregated structures. *CIRP J Manuf Sci Technol* 7(1):20–28. <https://doi.org/10.1016/j.cirpj.2013.10.001>
5. Bikas H, Lianos AK, Stavropoulos P (2019) A design framework for additive manufacturing. *Int J Adv Manuf Technol*:1–15. <https://doi.org/10.1007/s00170-019-03627-z>
6. Gibson I, Khorasani AM (2019) Metallic additive manufacturing: design, process, and post-processing. *Metals* 9(2):137. <https://doi.org/10.3390/met9020137>
7. Gibson I, Rosen DW, Stucker B (2014) *Additive manufacturing technologies*. Springer, New York
8. Schmidt M, Merklein M, Bourell D, Dimitrov D, Hausotte T, Wegener K, Overmeyer L, Vollertsen F, Levy GN (2017) Laser based additive manufacturing in industry and academia. *CIRP Ann* 66(2):561–583. <https://doi.org/10.1016/j.cirp.2017.05.011>
9. Kempen K, Vrancken B, Buls S, Thijs L, Van Humbeeck J, Kruth JP (2014) Selective laser melting of crack-free high density M2 high speed steel parts by baseplate preheating. *J Manuf Sci Eng* 136(6):061026–061026-6. <https://doi.org/10.1115/1.4028513>
10. Kruth JP, Vandenbroucke B, Van Vaerenbergh J, Mercelis P (2004) Selective laser melting of iron-based powder. *J Mater Process Technol* 149:612–622. <https://doi.org/10.1016/j.jmatprotec.2003.11.051>

11. Kalentics N, Sohrabi N, Tabasi HG, Griffiths S, Jhabvala J, Leinenbach C, Burn A, Loge RE (2019) Healing cracks in selective laser melting by 3D laser shock peening. *Addit Manuf* 1(30): 100881. <https://doi.org/10.1016/j.addma.2019.100881>
12. Levy GN, Schindel R, Kruth JP (2003) Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state of the art and future perspectives. *CIRP Ann* 52(2):589–609. [https://doi.org/10.1016/S0007-8506\(07\)60206-6](https://doi.org/10.1016/S0007-8506(07)60206-6)
13. Levy GN (2010) The role and future of the laser technology in the additive manufacturing environment. *Phys Procedia* 5:65–80. <https://doi.org/10.1016/j.phpro.2010.08.123>
14. Ding D, Pan ZS, Cuiuri D, Li H (2014) A tool-path generation strategy for wire and arc additive manufacturing. *Int J Adv Manuf Technol* 73(1–4):173–183. <https://doi.org/10.1007/s00170-014-5808-5>
15. Kruth JP, Levy G, Klocke F, Childs THC (2007) Consolidation phenomena in laser and powder-bed based layered manufacturing. *CIRP Ann* 56(2):730–759. <https://doi.org/10.1016/j.cirp.2007.10.004>
16. Qattawi A, Alrawi B, Guzman A (2017) Experimental optimization of fused deposition modelling processing parameters: a design-for-manufacturing approach. *Procedia Manuf* 10:791–803. <https://doi.org/10.1016/j.promfg.2017.07.079>
17. Ding D, Pan Z, Cuiuri D, Li H, van Duin S (2016) Advanced design for additive manufacturing: 3D slicing and 2D path planning. In: *New Trends in 3D Printing*. IntechOpen. <https://doi.org/10.5772/63042>
18. Dunbar AJ, Denlinger ER, Heigel J, Michaleris P, Guerrier P, Martukanitz R, Simpson TW (2016) Development of experimental method for in situ distortion and temperature measurements during the laser powder bed fusion additive manufacturing process. *Addit Manuf* 2:25–30. <https://doi.org/10.1016/j.addma.2016.04.007>
19. Gibson I, Rosen D, Stucker B (2015) *Additive manufacturing technologies - 3D printing, rapid prototyping, and direct digital manufacturing*. Springer, New York
20. Papacharalampopoulos A, Bikas H, Stavropoulos P (2018) Path planning for the infill of 3D printed parts utilizing Hilbert curves. *Procedia Manuf* 21:757–764. <https://doi.org/10.1016/j.promfg.2018.02.181>
21. Torrado AR, Roberson DA (2016) Failure analysis and anisotropy evaluation of 3D-printed tensile test specimens of different geometries and print raster patterns. *J Fail Anal Prev* 16(1):154–164. <https://doi.org/10.1007/s11668-016-0067-4>
22. Dapogny C, Estevez R, Faure A, Michailidis G (2019) Shape and topology optimization considering anisotropic features induced by additive manufacturing processes. *Comput Methods Appl Mech Eng* 344:626–665. <https://doi.org/10.1016/j.cma.2018.09.036>
23. Clausen A, Aage N, Sigmund O (2016) Exploiting additive manufacturing infill in topology optimization for improved buckling load. *Engineering* 2(2):250–257. <https://doi.org/10.1016/J.ENG.2016.02.006>
24. Lu L, Sharf A, Zhao H, Wei Y, Fan Q, Chen X, Savoye Y, Tu C, Cohen-Or D, Chen B (2014) Build-to-last: strength to weight 3D printed objects. *ACM Trans Graph* 33(4):97–10. <https://doi.org/10.1145/2601097.2601168>
25. Iyibilgin O, Yigit C, Leu MC (2013) Experimental investigation of different cellular lattice structures manufactured by fused deposition modeling. In: *Proceedings of Solid Freeform Fabrication Symposium*, Austin, pp 895–907
26. Wu J, Aage N, Westermann R, Sigmund O (2018) Infill optimization for additive manufacturing—approaching bone-like porous structures. *IEEE Trans Vis Comput Graph* 24(2):1127–1140. <https://doi.org/10.1109/TVCG.2017.2655523>
27. Dreifus G, Goodrick K, Giles S, Patel M, Foster RM, Williams C, Kunc V (2017) Path optimization along lattices in additive manufacturing using the Chinese postman problem. *3D. Print Addit Manuf* 4(2):98–104. <https://doi.org/10.1089/3dp.2017.0007>
28. Baich L, Manogharan G, Marie H (2015) Study of infill print design on production cost-time of 3D printed ABS parts. *Int J Rapid Manuf* 5(3–4):308–319. <https://doi.org/10.1504/IJRAPIDM.2015.074809>
29. Park SC, Choi BK (2000) Tool-path planning for direction-parallel area milling. *Comput Aided Des* 32:17–25. [https://doi.org/10.1016/S0010-4485\(99\)00080-9](https://doi.org/10.1016/S0010-4485(99)00080-9)
30. Rajan V, Srinivasan V, Tarabanis KA (2001) The optimal zigzag direction for filling a two dimensional region. *Rapid Prototyp J* 7(5):231–241. <https://doi.org/10.1108/13552540110410431>
31. Jin YA, He Y, Fu JZ, Gan WF, Lin ZW (2014) Optimization of tool-path generation for material extrusion-based additive manufacturing technology. *Addit manufact* 1:32–47. <https://doi.org/10.1016/j.addma.2014.08.004>
32. Ding D, Pan Z, Cuiuri D, Li H, Larkin N (2016) Adaptive path planning for wire-feed additive manufacturing using medial axis transformation. *J Clean Prod* 133:942–952. <https://doi.org/10.1016/j.jclepro.2016.06.036>
33. Wu J, Wang CC, Zhang X, Westermann R (2016) Self-supporting rhombic infill structures for additive manufacturing. *Comput Aided Des* 80:32–42. <https://doi.org/10.1016/j.cad.2016.07.006>
34. Farouki RT, Koenig T, Tarabanis KA, Korein JU, Batchelder JS (1995) Path planning with offset curves for layered fabrication processes. *J Manuf Syst* 14(5):355–368. [https://doi.org/10.1016/0278-6125\(95\)98872-4](https://doi.org/10.1016/0278-6125(95)98872-4)
35. Yang Y, Loh HT, Fuh JYH, Wang YG (2002) Equidistant path generation for improving scanning efficiency in layered manufacturing. *Rapid Prototyp J* 8(1):30–37. <https://doi.org/10.1108/13552540210413284>
36. Li H, Dong Z, Vickers GW (1994) Optimal toolpath pattern identification for single island, sculptured part rough machining using fuzzy pattern analysis. *Comput Aided Des* 26(11):787–795. [https://doi.org/10.1016/0010-4485\(94\)90092-2](https://doi.org/10.1016/0010-4485(94)90092-2)
37. Foteinopoulos P, Papacharalampopoulos A, Stavropoulos P (2017) On thermal modeling of additive manufacturing processes. *CIRP J Manuf Sci Technol* 20:66–83. <https://doi.org/10.1016/j.cirpj.2017.09.007>
38. Hu D, Kovacevic R (2003) Modelling and measuring the thermal behaviour of the molten pool in closed-loop controlled laser-based additive manufacturing. *Proc Inst Mech Eng B J Eng Manuf* 217(4): 441–452. <https://doi.org/10.1243/095440503321628125>
39. Li Y, Gu D (2014) Parametric analysis of thermal behavior during selective laser melting additive manufacturing of aluminum alloy powder. *Mater Des* 63:856–867. <https://doi.org/10.1016/j.matdes.2014.07.006>
40. Roberts IA, Wang CJ, Esterlein R, Stanford M, Mynors DJ (2009) A three-dimensional finite element analysis of the temperature field during laser melting of metal powders in additive layer manufacturing. *Int J Mach Tools Manuf* 49(12–13):916–923. <https://doi.org/10.1016/j.ijmachtools.2009.07.004>
41. Zhang DQ, Cai QZ, Liu JH, Zhang L, Li RD (2010) Select laser melting of W–Ni–Fe powders: simulation and experimental study. *Int J Adv Manuf Technol* 51(5–8):649–658. <https://doi.org/10.1007/s00170-010-2641-3>
42. Song B, Dong S, Liao H, Coddet C (2012) Process parameter selection for selective laser melting of Ti6Al4V based on temperature distribution simulation and experimental sintering. *Int J Adv Manuf Technol* 61(9–12):967–974. <https://doi.org/10.1007/s00170-011-3776-6>
43. Yin J, Zhu H, Ke L, Lei W, Dai C, Zuo D (2012) Simulation of temperature distribution in single metallic powder layer for laser micro-sintering. *Comput Mater Sci* 53(1):333–339. <https://doi.org/10.1016/j.commatsci.2011.09.012>

44. Zeng K, Pal D, Gong HJ, Patil N, Stucker B (2015) Comparison of 3DSIM thermal modelling of selective laser melting using new dynamic meshing method to ANSYS. *Mater Sci Technol* 31(8): 945–956. <https://doi.org/10.1179/1743284714Y.0000000703>
45. Stavropoulos P, Foteinopoulos P, Papacharalampopoulos A, Tsoukantas G (2019) Warping in SLM additive manufacturing processes: estimation through thermo-mechanical analysis. *Int J Adv Manuf Technol* 104(1–4):1571–1580. <https://doi.org/10.1007/s00170-019-04105-2>
46. Pastras G, Fysikopoulos A, Giannoulis C, Chrysosolouris G (2015) A numerical approach to modeling keyhole laser welding. *Int J Adv Manuf Technol* 78(5–8):723–736. <https://doi.org/10.1007/s00170-014-6674-x>
47. Li L, Lough C, Replogle A, Bristow D, Landers R, Kinzel E (2017) Thermal modeling of 304L stainless steel selective laser melting. In *Proceedings of the ASME 2017 International Mechanical Engineering Congress and Exposition, Advanced Manufacturing*, Tampa, FL, USA 2017 (3–9): 1068–1081
48. Hu H, Argyropoulos SA (1996) Mathematical modelling of solidification and melting: a review. *Model Simul Mater Sci Eng* 4:371–396. <https://doi.org/10.1088/0965-0393/4/4/004>
49. Cernuschi F, Ahmaniemi S, Vuoristo P, Mäntylä T (2004) Modelling of thermal conductivity of porous materials: application to thick thermal barrier coatings. *J Eur Ceram Soc* 24(9):2657–2667. <https://doi.org/10.1016/j.jeurceramsoc.2003.09.012>
50. Carvalho MS, Martins AP, Santos TG (2019) Simulation and validation of thermography inspection for components produced by additive manufacturing. *Appl Therm Eng* 1(159):113872–113879. <https://doi.org/10.1016/j.applthermaleng.2019.113872>
51. ANSYS®, Ansys Workbench, Release 15

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.