Computationally efficient distortion prediction in Powder Bed Fusion Additive Manufacturing

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Abstract— *This work addresses the analysis and development of computationally efficient distortion prediction numerical methodologies applicable to powder bed based selective laser melting (SLM) process. Initially, state of the art of simplified distortion modelling methodologies based on finite element (FE) models is introduced. Existing methodologies are described in terms of complexity and applicability to SLM process.*

The methodology known as inherent shrinkage, previously developed for multipass welding processes, is applied to predict SLM process induced distortion in Inco 718 testing geometry (cantilever). An assessment about predictive capability of this simplified model based on correlation between numerical results and experimental measurements is performed. Experimental distortions are measured after cutting of base plate connected supports. Initially, the influence of meshing, layer activation and equivalent thermal loads is investigated in terms of prediction capability and computational cost. Subsequently, isotropic and non-isotropic thermal expansion coefficients (α) are considered in the FE-model definition. Results demonstrate that it is feasible to accurately predict the distortion induced by different scanning strategies (chess-board pattern, transversal stripes and longitudinal stripes) in short times. Current developments entail a cost-effective alternative for controlling and reducing distortions in SLM parts.

Keywords*— *Additive manufacturing, distortion prediction, inherent shrinkage, numerical modeling, powder bed fusion.

I. INTRODUCTION

In powder bed based additive manufacturing (AM) processes components are directly built up layer by layer. Both laser (SLM, DMLS, SLS…) and electron beam (EBM) heat sources are employed to locally melt thin layers of predeposited metallic powders which will shape the final part. Distortions are critical during AM of metallic parts, since they increase manufacturing costs, times and generate wastes and scraps. Currently, corrective measures are often not taken until production step and they are mainly based on trial an error approach. This experimental corrective approach lacks of efficiency, flexibility and cost-efficiency. Alternatively, preventive methods based on distortion prediction numerical methodologies can anticipate distortions even form the design stage and entail a powerful tool for part design and process optimization. However, this requires the development of new computationally efficient modelling strategies that can be applicable to real parts.

In Selective Laser Melting (SLM), the material is locally and rapidly heated above its melting temperature and then allowed to solidify and cool to form a dense geometry. Extremely high heating and cooling rates are obtained due to the highly concentrated nature of heat source, i.e., laser beam, and quick processing rates (typical scanning rates around 1 m/s). This involves large thermal gradients. Thereby, residual stresses and distortions are generated due to the local inherent nature of the process. Moreover, post-manufacturing processes, such as cutting of support structures, lead to redistribution of internal stresses and strain modifying as-build distortions.

From a physical point of view, SLM can be considered as a multipass micro welding process and many of its modelling challenges are related to the numerical modelling of multipass welding [1]. Therefore, welding modelling techniques can be ideally adapted to SLM. However, despite there are several validated finite element (FEM) based modelling strategies for multipass welding, their direct implementation to SLM process is not straightforward due to limitations on computational cost and model complexity. The manufacturing of a real part by SLM will usually requires hundreds of layers and thousands of small weld seams. Thus, conventional thermo-mechanical FEM simulation is not totally suitable for distortion prediction of SLM parts at least on conventional computer platforms.

Several attempts have already been performed with the aim of developing computationally efficient distortion prediction models of SLM parts. Already developed models are based on the activation of full layer or combination of layers at once [2][3][4]. In these models, a uniform heat input is introduced on the whole layer within each load step [2][5][4][6]. This simplification neglects temperature gradients in X-Y direction and does not take into account the effect of scan pattern (stripes, chess-board). Nevertheless, these simplified models have demonstrated good predictive capability in geometrically simple parts [7].

Recently, alternative modelling approaches have been developed with the idea of capturing the effect of scanning strategy. One innovative approach is based on the introduction of non-uniform heat input on layers [8]. Different methods for modelling non-uniform heat input have been proposed which increase the calculation time but are able to reproduce the thermal cycling in one layer.

Another significant approach is based on a multi-scale method which includes the calibration of the heat source at microscopic scale, the analysis of scanning strategy at mesoscopic scale and the mapping of resulting inherent strains (eigenstrain) into a macroscopic layer model model [1][9]. This allows replacing computationally costly thermo-mechanical simulations by a mechanical one.

The work presented in this paper is focused on the development and application of an alternative simplified SLM distortion prediction methodology based on inherent shrinkage approach. This methodology has been previously developed for the calculation of welding distortion of large parts [10]. Inherent shrinkage is a mechanical approach where no transient thermal analysis is involved. It assumes that the main driving force for distortion is the thermal contraction of the weld metal during cooling to room temperature, and distortion are generated as a consequence of the accommodation by the structure of this contraction. This approach involves that elements in one layer undergo a shrinkage that is equal and opposite to the thermal expansion when the metal is heated up to its melting temperature. Current work is focused on the application of this methodology and its evaluation in simple geometry Inco 718 part (cantilever). An assessment about predictive capability of this simplified model based on correlation between numerical results and experimentally measured distortion is performed. Both isotropic and non-isotropic thermal expansion coefficients (α) have been considered for the model development. Developed distortion prediction methodology will be useful to gain a deeper understanding of powder bed fusion processes, optimize process parameters, analyze the influence of scanning strategy and develop part designs which are more robust against distortion [11].

II. EXPERIMENTAL WORK

Cantilever shape specimens made of Inco 718 were fabricated by SLM. Geometry and dimensions in mm are shown in Fig. 1 and they match with specimens manufactured in ref [1].

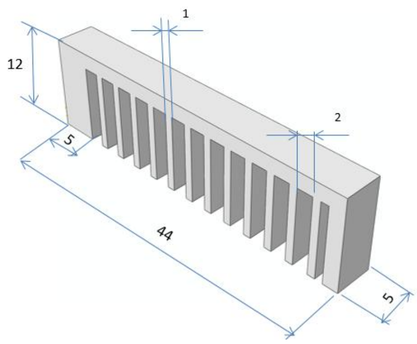


FIGURE 1: CANTILEVER SHAPE SPECIMEN WITH DIMENSIONS (MM)

Specimens were manufactured in state of the art SLM Solutions 280 HL machine equipped with 400 W fiber laser. Samples were manufactured using a layer thickness of 30 µm, 200 W and 120 µm hatch distance. Laser power was kept constant, but different scanning speeds were used for hatch (800 mm/s), boundary (1100 mm/s) and offset hatch (1100 mm/s). Preheating temperature was 25ºC.

Cantilever specimens were manufactured over thick baseplates (80 x 80 x 11 mm). Each baseplate contained 3 specimens built with the same process parameters but different scanning strategies (Fig. 2). Six baseplates were placed at the same time on the working platform of SLM machine, but on different locations, and a total number of 18 cantilevers (6 x 3 scanning strategies) were manufactured in the same batch.

Three different scanning strategies were investigated including chess-board pattern, transversal stripes and longitudinal stripes (Fig. 2). Squares of chess-board pattern were 7 mm size and the scanning direction was rotated 90º from one square to another. Stripes had a meandering pattern. From layer to layer, scanning strategy was kept constant.

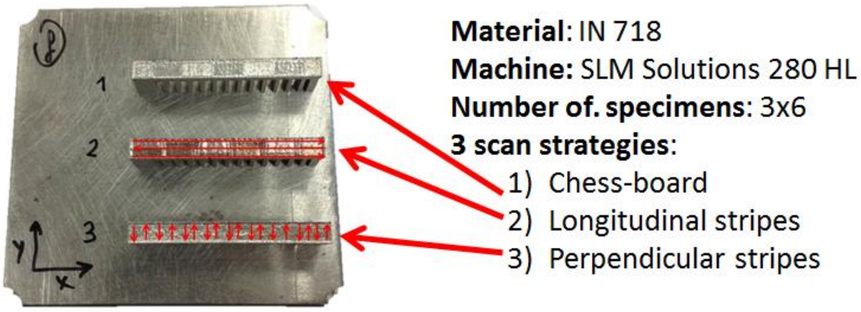


FIGURE 2: SCANNING STRATEGIES FOR THE MANUFACTURING OF CANTILEVER SPECIMENS IN ONE BASEPLATE. 6 EQUIVALENT BASE PLATES WERE MANUFACTURED IN THE SAME BATCH

After manufacturing, supports of cantilever specimens were cut from the baseplate by Electrical Discharge Machining (EDM). The thicker leg was left attached to the baseplate (Fig. 3). No thermal treatment was applied either before or after cutting and therefore, final distortion directly resulted from the redistribution of SLM process induced residual stresses. The final vertical distortions (Z component) were measured on the top-surface of cantilevers. Measuring points were located in the central longitudinal line along cantilever's length and keeping a constant distance of 5 mm between points. Distortions were measured on metrology flat table using dial gauge with 10 µm accuracy.

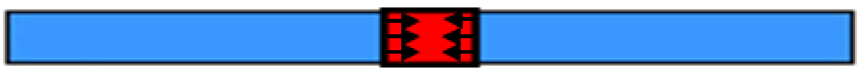
FIGURE 3: SUPPORT CUTTING FORM THE BASE PLATE BY EDM AND RESULTING DISTORTION

III. NUMERICAL MODEL

3.1 Inherent shrinkage methodology

The inherent shrinkage is a mechanical elasto-plastic calculation where no thermal analysis is involved. Material properties are not considered temperature dependent. Main assumption of this methodology is that the main driving force for distortion is the linear thermal contraction of the melted metal on cooling. In welding applications, it is assumed that the material that is melted (weld bead) undergoes a equivalent thermal strain whose magnitude can be calculated by multiplying the material's thermal expansion coefficient and the temperature gap between surrounding material and melt pool. The inherent shrinkage methodology considers that this equivalent thermal strain must be accommodated by the part leading to a redistribution of stresses and strains.

The mathematical equation of this approach is included in Fig. 4, where ε^{th} is the equivalent thermal strain, α is the thermal expansion coefficient and ΔT is the temperature gradient. The application of this methodology requires the adjustment of the volume of shrinking elements and their initial temperature [10]. After determining and mapping equivalent thermal strains in welded structures, a pure mechanical elasto-plastic analysis is performed leading to the final distortion.



$$\varepsilon^{th} = \alpha \cdot \Delta T$$

FIGURE 4: EQUIVALENT THERMAL STRAIN CONSIDERED FOR THE IMPLEMENTATION OF INHERENT SHRINKAGE METHODOLOGY

Due to the layer by layer nature of powder bed fusion processes, the following assumption has been done in this work for the transference of inherent shrinkage methodology to AM: elements included in one layer will undergo a shrinkage related to their thermal expansion when the metal is heated up to its melting temperature. Therefore, a full layer activation strategy has been adopted which can greatly reduce FE-model complexity and computational costs in comparison with discrete shrinking elements.

3.2 Inherent shrinkage based FE-model

A FE-model was defined to assess predictive capability of inherent shrinkage methodology in cantilever geometry. Abaqus 6.14-2 software was employed for the implementation of new numerical methodology. The geometry was meshed using 182098 C3D8R hexaedral elements. A layer-based meshing procedure was applied which gave rise to a mesh composed by parallel layers in the building direction one of top of each other (Fig. 5). The original mesh of the cantilever specimen had in total 100 layers (120 µm thickness), each of them containing two elements in the thickness direction.

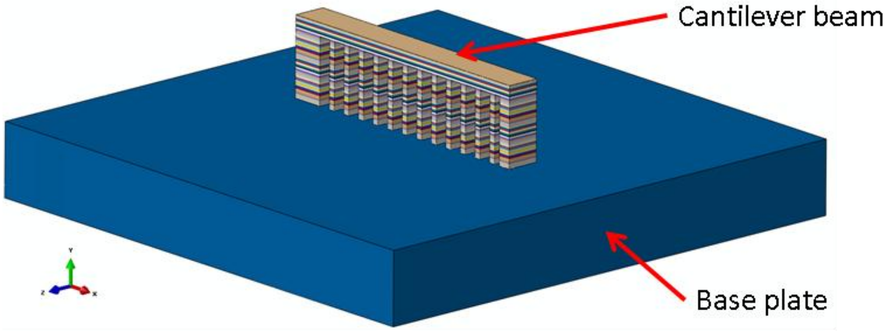


FIGURE 5: FE-MODEL OF CANTILEVER SAMPLE

Temperature independent Inco 718 material properties were introduced in the FE-model (Table 1). Elasto-plastic material behaviour was selected.

TABLE 1
INCO 718 MATERIAL PROPERTIES

Mechanical properties	Value
Density (kg/m3)	8146
Young modulus (MPa)	210000
Poisson coefficient	0.38
Yield strength (MPa)	700
Ultimate strength (MPa)	900

Concerning the thermal expansion coefficient, α, three different approaches were considered including isotropic and non-isotropic (orthotropic) behaviour in vertical and transversal directions. Next table summarizes the 3D components of the thermal expansion coefficient that were used in different models. Vertical component was parallel to building direction (Z), longitudinal to the length of the cantilever (X) and transversal to the width of the cantilever (Y). Moreover, the effect of the initial melting temperature defined for the introduction of equivalent thermal loads was studied. Initial temperatures that were selected for the activation of new layers were between 1000 and 2000ºC.

TABLE 2
COMPONENTS OF THERMAL EXPANSION COEFFICIENTS USED IN DIFFERENT MODELS

	Vertical (Z)	Longitudinal (X)	Transversal (Y)
Model I – Isotropic $\alpha_{xx} = \alpha_{yy} = \alpha_{zz} = \alpha$	$1.28 \cdot 10^{-5}$	$1.28 \cdot 10^{-5}$	$1.28 \cdot 10^{-5}$
Model II – Orthotropic (longitudinal) $\alpha_{xx} = 2\alpha\, ;\, \alpha_{yy} = \alpha_{zz} = \alpha$	$1.28 \cdot 10^{-5}$	$2.56 \cdot 10^{-5}$	$1.28 \cdot 10^{-5}$
Model III – Orthotropic (transversal) $\alpha_{yy} = 2\alpha\, ;\, \alpha_{xx} = \alpha_{zz} = \alpha$	$1.28 \cdot 10^{-5}$	$1.28 \cdot 10^{-5}$	$2.56 \cdot 10^{-5}$

The sequential activation of elements lying on discrete layers was modelled by using the so called "birth and death" or model change technique. According to this activation strategy, elements are not part of the model until they are activated [12]. Inherent shrinkage was implemented by introducing equivalent thermal loads in the FE-model in selected stacks of meshing layers at the same time. Different number or combinations of layers of FE-model mesh were activated in each step with the aim of studying the effect of this activation procedure on the distortion prediction capability and computational cost. Note that real cantilever specimens were manufactured in 400 layers, with 30 µm thickness each one. The simulation of the real number of layers would require very small size elements in the building direction, a huge amount of elements and long computational times. Alternatively, if the number of sequentially activated layers is reduced, the computational time will decrease. Thus, the layer activation in the FE-model was discretized in different number of layers in the building direction, i.e, 5, 10, 50 and 100 activation steps, corresponding to 2400 µm, 1200 µm, 240 µm and 120 µm layer thicknesses (Fig. 6).

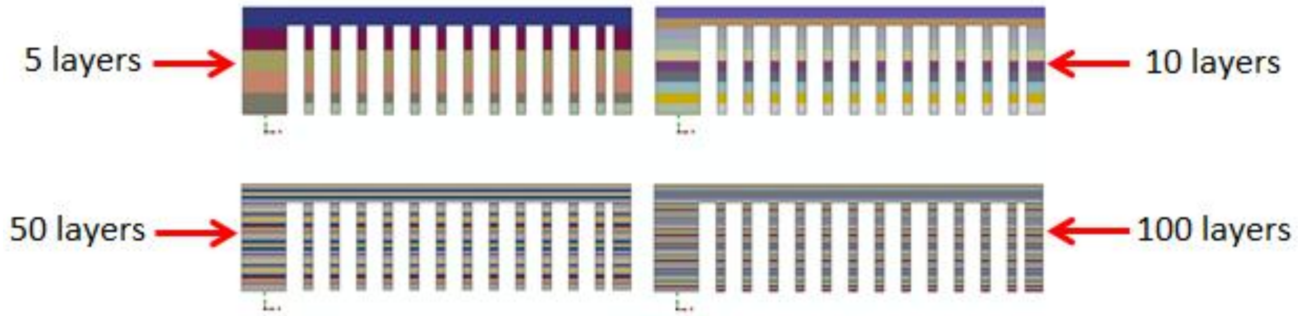


FIGURE 6: FE-MODELS WITH DIFFERENT SEQUENTIAL NUMBER OF LAYER ACTIVATION STEPS

Both simulated residual stresses after completing activation of every model layer and final distortions after cutting of the supports from the baseplate were analysed.

IV. RESULTS AND DISCUSSION

4.1 Experimentally measured distortion

Fig. 7 shows experimental distortion along vertical direction that were measured in manufactured cantilever specimens after EDM cutting. Mean values and standard deviations measured in 10 control points along cantilever's length of 6 samples manufactured with the same scanning strategy are depicted. It must be noted the consistency and repetitiveness of the experimental results, which leads to the conclusion that there is not an influence on the relative placing of samples on the SLM machine platform.

On the other hand, a great influence of the scanning strategy on final distortion can be observed. Scanning strategy with longitudinal stripes led to the highest distortion, whereas transversal stripes reduced them. These results are consistent with previously reported ones [1]. These experimental measurements were considered for the validation of new simplified distortion prediction

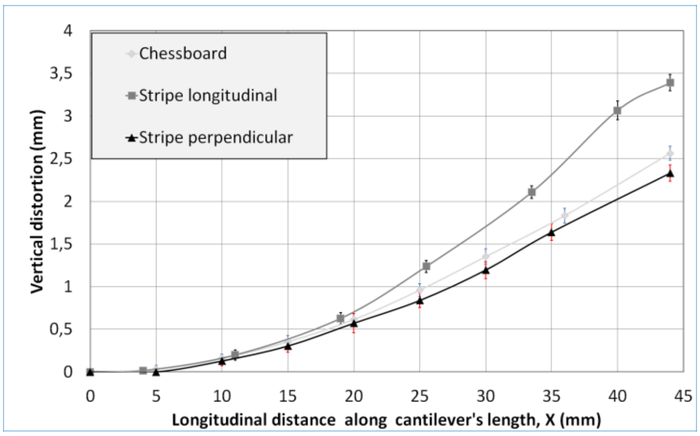


FIGURE 7: EXPERIMENTALLY MEASURED VERTICAL DISTORTION OF CANTILEVER SPECIMENS MANUFACTURED WITH DIFFERENT SCANNING STRATEGIES.

4.2 Numerical results from inherent shrinkage FE-models

4.2.1 Influence of layer activation steps

Fig. 8 represents distortion predicted by isotropic FE-model (Model I) using different number of layer activation steps. The results show that at least 50 layer activation steps, corresponding to 240 µm equivalent layer thickness, are required in the FE-model in order to obtain a good matching between numerical and experimental results. The distortion prediction of FE-models with 50 and 100 layer activation steps was in good correlation with experimental results obtained using the chess-board scanning strategy.

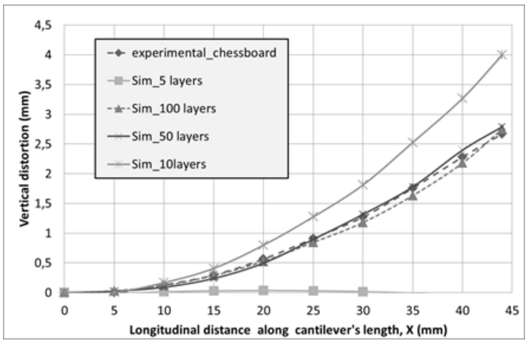


FIGURE 8: COMPARISON OF PREDICTED VERTICAL DISTORTION ALONG CANTILEVER LENGTH WITH EXPERIMENTAL MEASUREMENTS (CHESS-BOARD SCANNING STRATEGY)

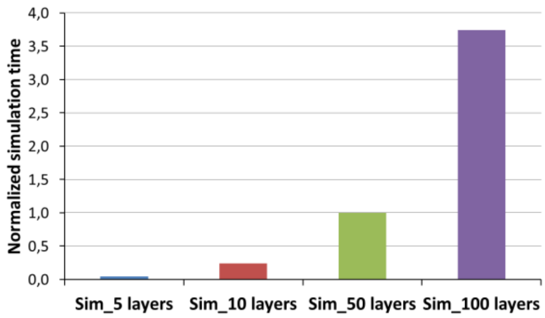


FIGURE 9: NORMALIZED SIMULATION TIME WITH DIFFERENT NUMBER OF LAYER ACTIVATION STEPS.

In terms of computational cost, the time required for model resolution was 2.3 hours for the 50 layers model. This time was recorded in an Intel Core i7-3770 3.40 GHz microprocessor with 4 CPUs. This time was used for the determination of the normalized simulation time and comparison of different number of layer activation steps (Fig. 9). As it can be observed, the introduction of 100 activation layer steps increases the computational time by 3.5 times, but it does not entail a significant improvement on the prediction capability. It must be noted, that the optimum layer activation thickness that has been determined (240 µm) represents 8 layers in the real SLM process (30 µm). Recent studies have experimentally demonstrated that real weld seam depth in SLM process can be 5-6 times the layer thickness selected on the manufacturing data set [13]. That means that not only the last deposited powder layer is melted, but underlying and already solidified layers are also remelt.

4.2.2 Influence of initial temperature

Concerning the influence of the initial temperature defined in the isotropic model (Model I) with 50 layer activation steps, no differences were observed between 1000 and 2000ºC in final distortion (Fig. 10). Surprisingly, the distortion predicted by 3 models with different initial temperatures were similar. This could be considered as an inconsistent result since initial temperature significantly affects distortion on welding applications. However, current results can be explained taking into account that final distortion are simulated after cutting cantilever’s supports. Cutting generates a redistribution of residual stresses that are stored in the part during SLM buildup manufacturing process. The analysis of modelled residual stresses and plastic strains before support cutting shows that the distribution and magnitude of residual stresses were comparable for the three studied initial temperatures (Fig. 11). Therefore, final distortion after residual stress redistribution will be similar.

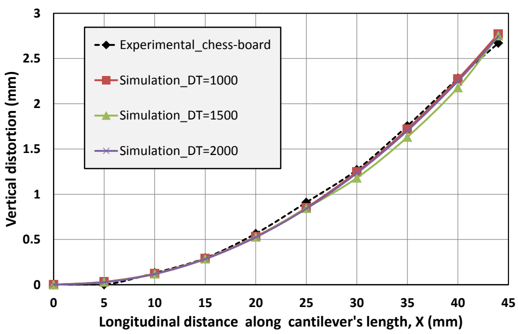
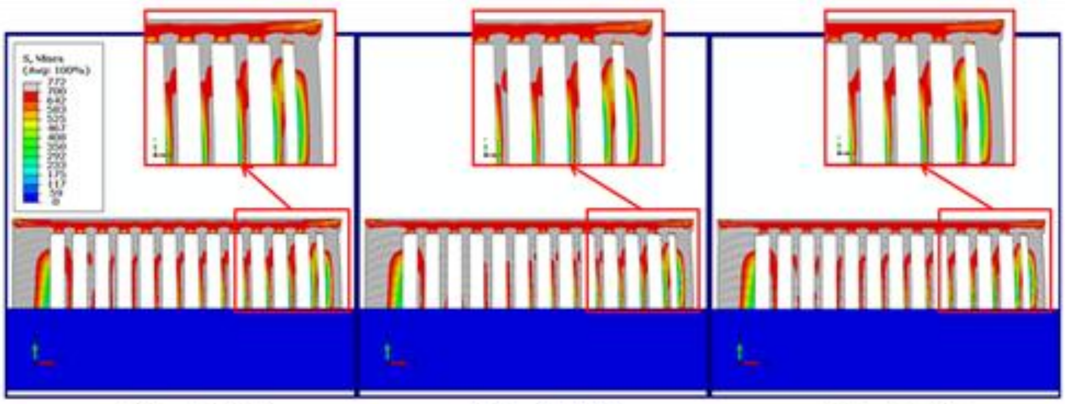


FIGURE 10: COMPARISON OF PREDICTED VERTICAL DISTORTION ALONG CANTILEVER LENGTH AFTER INTRODUCING DIFFERENT INITIAL TEMPERATURES.



$\Delta T_1 = 1000K$ $\Delta T_2 = 1500K$ $\Delta T_3 = 2000K$

FIGURE 11: RESIDUAL STRESSES BEFORE CUTTING PROCESS PREDICTED BY ISOTROPIC NUMERICAL MODEL FOR DIFFERENT INITIAL TEMPERATURES.

4.2.3 Influence of thermal expansion coefficient

As it is shown in Fig. 7, experimental distortion mainly depend on the scanning strategy. Results of predicted distortion considering both isotropic and orthotropic thermal expansion coefficients are shown in Fig. 12.

As stated before, distortion obtained with chess-board scanning strategy can be accurately predicted using isotropic thermal expansion coefficient (model I). Maximum difference between experimental and numerical results is lower than 0.22 mm.

Model II with a higher thermal expansion coefficient in the longitudinal direction (X component) yields vertical distortion results that match with the experimental results obtained in cantilevers manufactured with the longitudinal stripes scanning strategy. Moreover, Model III, with a higher thermal expansion coefficient in transversal direction gives rises to lower distortion that come very close to the experimental results for samples manufactured with transversal stripes. Deviation between experimental results and numerical prediction are lower than 0.43 mm and 0.15 mm, respectively. It must be noted that these models effectively predict both shape and magnitude of the curve describing vertical distortion along cantilever's length.

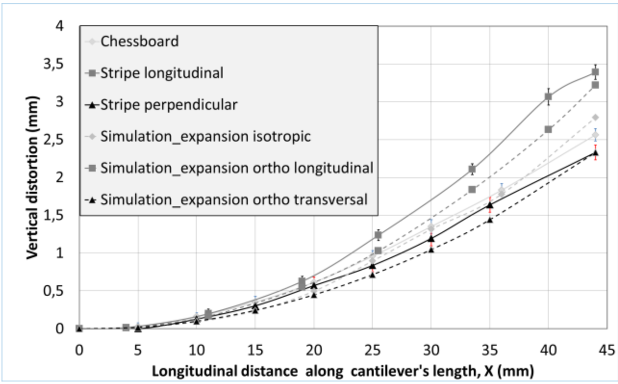


FIGURE 12: COMPARISON OF EXPERIMENTAL VS SIMULATION DISTORTIONS WITH DIFFERENT THERMAL EXPANSION COEFFICIENTS (ISOTROPIC AND ORTHOTROPIC)

V. CONCLUSION

Inherent shrinkage simplified numerical methodology has been successfully applied to powder bed fusion SLM process. This new computationally efficient methodology is suitable for the fast and accurate prediction of real components and has been validated in real simple geometry (cantilever) by comparing model results with experimentally measured distortion.

This methodology requires the definition of a FE-model with a sequential activation of layers ("birth and death" or model change technique). A minimum number of layer activation steps is required in order to ensure good prediction. For the geometry studied in this work a good prediction was achieved for a ratio between real manufacturing layers and model layer activation steps of 8 (400 real layers, activated in 50 steps). Above this ratio, the predictive capability decreases, whereas the increase of this ratio does not improve the accuracy of the results, but increases computational cost.

Experimental distortion mainly depend on scanning strategy (chess-board, transversal stripes, longitudinal stripes). Despite the simplicity of the model, it was feasible to predict the distortion using different scanning strategies. Good correlation with chess-board scanning strategy was obtained by applying isotropic model (no differences in the 3D components of the thermal expansion coefficients), whereas, close matching with both longitudinal and transversal stripe scanning strategies was attained by orthotropic models (higher thermal expansion coefficient in longitudinal or transversal direction).

Current results support the idea that inherent shrinkage methodology can be a computationally efficient tool for fast distortion prediction in powder bed fusion AM processes. A next step towards the implementation of this methodology should be to transfer to more complex parts.

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