

# Investigating Simulation Approaches for Distortion in Thin-Walled Components During the Selective Laser Melting Process

Mohammad Waleed<sup>1,\*</sup>, Aqeel Ahsan Khurram<sup>2</sup>, Muhammad Ahsan Kaleem<sup>1</sup> and Atique Ahmad<sup>1</sup>

<sup>1</sup>Department of Mechanical Engineering, Pakistan Institute of Engineering and Applied Sciences, Islamabad, Pakistan

<sup>2</sup>Pakistan Institute of Additive Manufacturing (PIAM3D), National Center for Physics, Islamabad, Pakistan

\*Corresponding author: [mohammadwaleed@protonmail.com](mailto:mohammadwaleed@protonmail.com)

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## Abstract

The inherent challenge of part distortion during the Selective Laser Melting (SLM) process remains a significant concern, especially for thin-walled structures. Various simulation strategies predict part distortion before 3D printing, saving material, time and cost. This work focuses on simulation methodologies for predicting distortion in thin-walled components. We used single-layer, multi-track meso-scale simulation, incorporating Gaussian heat flux and accounting for phase and material property changes, to predict inherent strains. We compared distortion predictions for square, cylindrical, and single-walled structures using four approaches: isotropic yield strain, thermal shrinkage strain, experimental strain, and meso-scale-obtained strains. The results showed that isotropic yield strain, while tending to overestimate distortion, was suitable for generating qualitative distortion profiles for symmetric thin-walled structures such as single-walled, square, and cylindrical ones. It also proved valuable for comparative studies in part-level simulation with distinct geometrical parameters. For square-walled structures, width was identified as the primary driver of distortion, with increasing width leading to a nearly linear increase in distortion. Cylindrical thin-walled structures exhibited lower deformation compared to square sections. Increasing diameter and height increased distortion, while distortion slightly decreased when thickness increased from 0.5 to 2 mm. In single-walled structures, wall width was the dominant factor affecting distortion.

**Keywords:** Metal Additive Manufacturing, Gaussian Heat Flux, Inherent Strain, Selective Laser Melting

## Introduction

Metal additive manufacturing, a transformative technology, holds immense potential to revolutionize traditional manufacturing processes by enabling precise, highly customizable, and resource-efficient production of metal components. Intricate metal parts that would otherwise be impossible to produce by conventional manufacturing can be reliably built by the selective laser melting (SLM) process [1, 2]. Because SLM has extremely high cooling rates (up to 108 K/s), it induces thermal stresses that transform into residual stresses in the component [3, 4]. Distortion, warpage, and cracking occur when these residual stresses exceed the material's yield limit. Thin-walled structures, due to their low structural stiffness and rigidity, are a concern and current research trends toward distortion-free SLM fabrication [5, 6, 7].

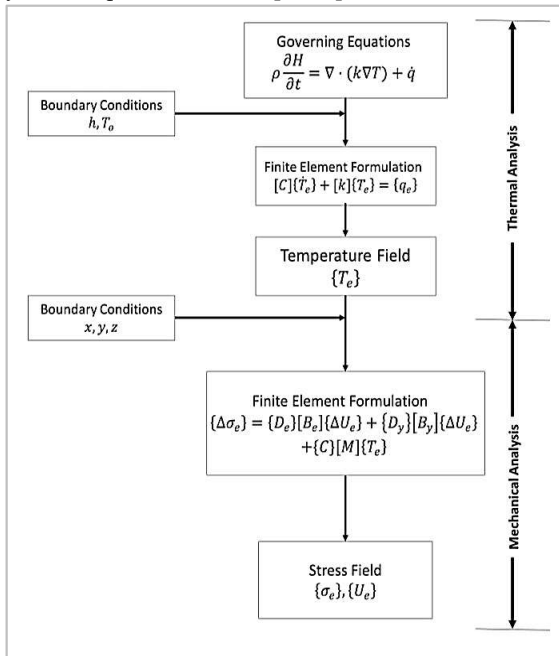
Simulation of the Selective Laser Melting (SLM) process is a highly efficient alternative to repetitive experimentation, significantly reducing time and costs [8]. Peter et al. [9] introduced various simulation strategies, including multi-scale modeling and inherent strain-based modeling, which the SLM simulation software industry widely embraces. For distortion and residual stress analysis, a transient thermo-structural FEM model is widely adopted, but complex boundary conditions and very thin ( $\sim 40 \mu\text{m}$ ) layer-by-layer printing make it extremely time-consuming and computationally inefficient; thus, this method is used when simulating only a few layers [8]. The inherent strain methodology is the most widely used SLM simulation method because of its efficiency and accuracy. Fabricating thin-walled structures through SLM is extremely challenging because low structural stiffness and heat dissipation rate cause excessive distortion. Simulation studies are therefore highly significant for manufacturing thin-walled structures through SLM. Xu et al. [7] used a staggered thermo-mechanical

model with the thermal shrinkage method to simulate distortion in thin-walled structures. Quasi-plane stress conditions and negligible  $\epsilon_z$  are assumed due to the thinness of the structures, considering uniform inherent strains across the cross-section line, disregarding the scan pattern. Vastola et al. [10] used the inherent strain methodology for simulation and parametric study of a thin tubular structure, where Hill's criterion is used to obtain inherent strains ( $\epsilon^* = -0.004875$ ). Yaghi et al. [11] employed the inherent strain method for elastic and elastic-plastic analysis of a double cantilever beam specimen. Inherent strains equal to the yield strain at room temperature are employed in the study. Alvarez et al. [12] employed thermal strains evaluated by CTE ( $\alpha$ ) times the temperature difference to study deformation in a cantilever beam while using three different models for evaluation of CTE. Setien et al. [13] used an empirical methodology to determine inherent strains for Ti6Al4V alloy and concluded that the inherent strain matrix is orthogonal. Zhonghua et al. [14] investigated the effect of scan length on thin-walled structure fabrication through meso-scale simulation and experimentation. They concluded that to be between 40-60 mm for minimum possible distortion. Qian et al. [15] obtained inherent strains ( $\epsilon_x, \epsilon_y, \epsilon_z$ ) from thermo-structural micro-scale tri-layer analysis of moving laser heat sources, aiming to eliminate the experimentation required to obtain these three strains for every set of process parameters. A more refined work in which Taufek et al. [16] obtained inherent strains by performing thermo-mechanical simulation, followed by virtual calibration of those inherent strains using SimuFact Additive and finally using calibrated/optimized inherent strains in part-scale simulation and experimentation of a cylindrical specimen. Simulating thin-walled structures differs from other simulations because they involve buckling, low structural stiffness, etc. A comparative study of various inherent-strain methodologies used in the literature needs to be performed for thin-walled structures.

The current work involves a comparative analysis of four distinct methods for predicting inherent strain for part-level SLM simulation: meso-scale-based IS, experimentally calibrated IS, thermal shrinkage strains, and isotropic inherent strains for three thin-walled structures; single wall, square, and circular configurations.

### Simulation Methodology for SLM Process

The SLM process selectively melts thin powder layers repetitively to form the desired part. Inclusion of all physical, thermal and structural phenomena like convection, radiation and laser heat source movement for part-scale simulation in layer-by-layer fashion (~20-40-micron layer height) is computationally very expensive. It is only possible for thin structures with small height [9]. The inherent strain methodology uses a lumped-layer approach in which several layers are lumped together, and inherent strain is applied to each layer [17]. Because thermal phenomena are repetitive and similar in each layer, thermal simulation is omitted, and inherent strains obtained experimentally, analytically, or by meso-scale simulation are used, reducing thermo-mechanical analysis to a quasi-static one [9, 13].



**Figure 1:** Governing equations and simulation workflow. In IS-based analysis, the focus is on conducting a structural analysis of the 3D-printed part using inherent strains as input parameters. The analysis is performed layer by layer, using the element birth/death technique to simulate the sequential printing process. The inherent strains in the x, y, and z directions are specified as input parameters to represent the residual stresses and deformations within the printed part. Each layer is activated individually, and the corresponding elements within that layer are subjected to the prescribed x-, y-, and z-directed strains using the INISTATE command. This step ensures that the inherent strains are applied

accurately for each layer. The analysis simplifies the strain tensor by neglecting shear components, as they are considered to have minimal effects in Selective Laser Melting (SLM) inherent strain-based simulations [18].

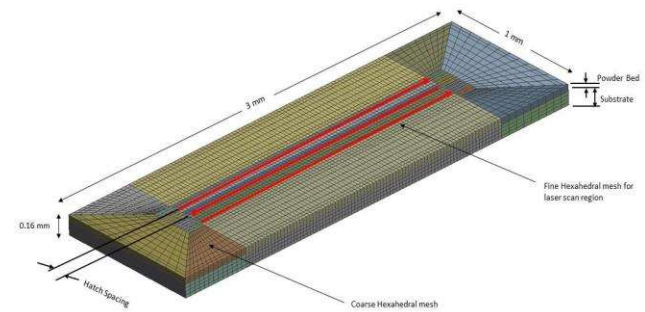
Implementing inherent strain to model layer-by-layer element activation involves two methodologies. First, by setting the  $\alpha$  (CTE) value equal to the strain magnitude and giving a  $\Delta T$  of 1oC [15], and the second method is to alter strain values in the FEM software strain matrix [19]. Current work implements inherent strains in ANSYS Workbench using the INISTATE command. The product of SSF and yield strain evaluates inherent strains ( $\epsilon_x, \epsilon_y, \epsilon_z$ ).

$$\epsilon = SSF \cdot \frac{\sigma_y}{E} \quad (1)$$

#### 1) Meso-Scale Model-Based Inherent Strain

ANSYS offers an effective approach for analyzing thermal and structural aspects in Selective Laser Melting (SLM). Initially, a nonlinear transient thermal analysis captures the overall temperature history of tracks induced by laser exposure. In stress analysis, the thermal loads derived from the preceding thermal analysis are input into the static structural model. A 3D meshed model represents the powder layer during SLM, as depicted in Figure 2. For optimal precision and computational efficiency, we use 20  $\mu\text{m}$  hexahedral elements in the laser-tracking area, while a skewed, coarser mesh is used for the surrounding powder.

Table 1 outlines the parameters used in the current FE analysis. The meso-scale simulation will provide the temperature history of laser tracks and the inherent strains ( $\epsilon_x, \epsilon_y, \epsilon_z$ ), which are to be used for part-scale inherent strain simulation in ANSYS Workbench.



**Figure 2:** Mesoscale finite element model

Mesoscale simulation requires temperature-dependent material properties of Ti6Al4V (powder, liquid, solid), tabulated in Table 2, as well as process parameters such as scanning speed and laser power.

**Table 1:** Process parameters for mesoscale simulation

| Parameter              | Value     |
|------------------------|-----------|
| Laser Power, P         | 300 W     |
| Heat source absorption | 0.24 [20] |
| Scan Speed, v          | 1000 mm/s |

|                                     |                       |
|-------------------------------------|-----------------------|
| Scan length, l                      | 1.8 mm                |
| Hatch spacing, h <sub>s</sub>       | 0.08 mm               |
| Tracks, n                           | 3                     |
| Powder thickness, t                 | 40 μm                 |
| Laser beam diameter, d <sub>o</sub> | 0.08 mm               |
| Thermal element                     | Solid 70              |
| Surface effect element              | Surf 152              |
| Structural element                  | Solid 186             |
| Preheating temperature              | 35°C                  |
| Convection coefficient, h           | 8 W/m <sup>2</sup> .K |

### • Thermal Modelling

The governing Fourier equation used for thermal analysis, assuming isotropic medium conductivity, is shown below.

$$\rho c_p \frac{dT}{dt} = \frac{\partial}{\partial x} \left( k(T) \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k(T) \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k(T) \frac{\partial T}{\partial z} \right) + q_s \quad (2)$$

$$\rho c_p \frac{dT}{dt} = k(T) \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + q_s \quad (3)$$

The material density,  $\rho$  is the specific heat capacity, and  $k(T)$  is the temperature-dependent thermal conductivity.  $q_s$  represents any heat generation or absorption within the material.

### • Laser Heat Source

In SLM modeling, the heat source model describes laser radiation absorption, which is critical for predicting the temperature time history of laser tracks. This work employs Gaussian heat flux (TEM00 mode), which various researchers use to simulate laser powder bed fusion [3, 14, 21]. Gaussian heat flux, represented as a function of  $x$ ,  $y$ , and time, is given as follows.

$$Q(x, y, t) = \frac{2AP}{\pi r_0^2} e^{-2(x^2 + (y-v.t)^2)/r_0^2} \quad (4)$$

where  $r_0$  indicates the radius at which the laser beam intensity reduces to  $1/e^2$  of its initial value.

### • Boundary Conditions

The model's initial temperature is set to 35 °C. The substrate is maintained at 35 °C throughout the laser scanning and cooldown process.

Convection, one of the main sources of heat transfer after conduction in SLM, is applied after the laser scans the surface because SURF 152 elements in Ansys apply only heat flux or convection simultaneously and ignore the others. Therefore, a convection coefficient of 8 W/m<sup>2</sup>. K is applied to the entire powder bed surface after the laser scan is complete.

$$-k \frac{\partial T}{\partial z} = h(T_s - T_a) \quad (5)$$

Where  $T_s$  is the surface temperature, and  $T_a$  is the ambient temperature.

The transient thermal analysis is divided into several steps because material properties change at each load step based on node temperature. An APDL subroutine was added to

simulate the Gaussian heat loading as a function of  $x$ ,  $y$ , and time. In this work, the laser scanning direction is the  $Y$  direction. Another APDL subroutine was proposed to identify elements whose temperatures exceed the melting point and convert those elements from powder to bulk material. In this way, a closely representative FEM model of the SLM process is being prepared and analyzed. The full Newton-Raphson method was employed to account for the non-linearity in the FEM model. Line search was set to ON because the FEM model involved a phase-change phenomenon.

### • Structural Modelling

The temperature profile obtained from the single-layer simulation was input into the structural FEM model for quasi-structural analysis. The bottom of the substrate is fixed, and the only load is the imported temperature load at different time steps from the thermal analysis.

To obtain inherent strains from the meso-scale simulation, we evaluated the strains from track 2, since the central track experienced the maximum thermal gradient throughout the laser scan. The load is mapped to the structural mesh appropriately to account for stress and deformation in the model.

The bottom face of the substrate is fixed in all degrees of freedom while the temperature load for various load steps (with a start and increment of  $1e^{-5}$  s) is applied/mapped. The next section presents the detailed methodology and strain evaluation.

In the melting and solidification stages of the Additive Manufacturing (AM) process, the cumulative strains, represented as  $\epsilon^{\text{total}}$ , can be divided into various components. These components include elastic strains  $\epsilon^{\text{elastic}}$ , plastic strains  $\epsilon^{\text{plastic}}$ , thermal strains  $\epsilon^{\text{thermal}}$ , strains caused by the phase-change phenomenon  $\epsilon^{\text{phase}}$ , and creep strains  $\epsilon^{\text{creep}}$ .

$$\epsilon^{\text{total}} = \epsilon^{\text{elastic}} + \epsilon^{\text{thermal}} + \epsilon^{\text{plastic}} + \epsilon^{\text{phase}} + \epsilon^{\text{creep}} \quad (6)$$

The inherent strains  $\epsilon^{\text{inh}}$  are characterized as follows,

$$\epsilon^{\text{inh}} = \epsilon^{\text{total}} - \epsilon^{\text{elastic}} = \epsilon^{\text{thermal}} + \epsilon^{\text{plastic}} + \epsilon^{\text{phase}} + \epsilon^{\text{creep}} \quad (7)$$

Equation 8 represents the force balance for a static analysis.

$$\nabla \cdot \sigma + b = 0 \quad (8)$$

where  $\sigma$  represents the stress tensor and  $b$  depicts the body forces. The corresponding stress can be calculated using the constitutive relation.

$$\sigma = D^e \epsilon^{\text{elastic}} = D^e (\epsilon^{\text{total}} - \epsilon^{\text{inh}}) \quad (9)$$

where  $D^e$  denotes the elastic tensor.

The inherent strain evaluated is the sum of the plastic strain just after the laser scan ( $\epsilon^{\text{pl}}$ , intermediate) and the difference between the intermediate and after-cooling elastic strains. All other shear strain components are neglected.

$$\epsilon^{\text{inh}} = \epsilon^{\text{Plastic}}_{\text{intermediate}} + \epsilon^{\text{Elastic}}_{\text{intermediate}} - \epsilon^{\text{Elastic}}_{\text{cool-down}} \quad (10)$$

The resulting inherent strain is applied to the part-scale simulation model. [15]

### • Material Properties

In thermo-mechanical analysis, most thermal and structural properties are temperature-dependent because of the large

temperature gradients and phase-change phenomena in SLM simulation. Assuming constant properties and disregarding temperature effects in the simulation cannot effectively capture the complex physical phenomena of the problem. The simulation uses temperature-dependent thermal properties such as specific heat, enthalpy, density, and conductivity, as given in the literature [14].

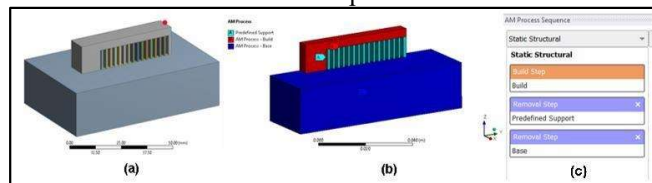
Temperature-dependent mechanical properties used for structural simulation are tabulated in Table 2.

**Table 2:** Mechanical properties of Ti6Al4V [22]

| Temperature<br>[°C] | $\alpha$<br>$1 \times 10^{-6}$<br>[1/K] | Young's<br>modulus<br>E | Yield<br>stress.<br>$\sigma_y$ | Plastic<br>tangent<br>modulus<br>$\sigma_p$ |
|---------------------|-----------------------------------------|-------------------------|--------------------------------|---------------------------------------------|
|                     |                                         | [GPa]                   | [MPa]                          | [GPa]                                       |
| 24.0                | 8.8                                     | 125.0                   | 1000.0                         | 0.7                                         |
| 94.0                | 9.8                                     | 110.0                   | 630.0                          | 2.2                                         |
| 205.0               | 10.0                                    | 100.0                   | 630.0                          | 2.2                                         |
| 317.0               | 10.7                                    | 100.0                   | 525.0                          | 2.2                                         |
| 428.0               | 11.1                                    | 80.0                    | 500.0                          | 1.9                                         |
| 539.0               | 11.2                                    | 74.0                    | 446.0                          | 1.9                                         |
| 650.0               | 11.7                                    | 55.0                    | 300.0                          | 1.9                                         |
| 761.0               | 12.2                                    | 27.0                    | 45.0                           | 2.0                                         |
| 872.0               | 12.3                                    | 20.0                    | 25.0                           | 2.0                                         |
| 1094.0              | 12.4                                    | 5.0                     | 5.0                            | 2.0                                         |
| 1650                | 12.5                                    | 0.1                     | 0.1                            | 0.1                                         |

## 2) Experimentally Calibrated Inherent Strain

Laser scanning measured the vertical distortion at the tip of the SLM-printed cantilever beam after support removal by wire EDM, and found it to be 0.996 mm. For calibration, a CAD model of the cantilever beam (L=50 mm, W=10 mm, and H=12.5 mm) for IS-based analysis was developed along with the support structure and base plate, as shown in Figure 3 (a). Moreover, the beam's half-symmetry is used, modeling only one half with symmetry boundary conditions to simulate the entire beam and reduce computational resources.



**Figure 3:** Simulation setup for experimental calibration of Inherent strain (a) CAD model of cantilever (b) Symmetric beam with boundary conditions (c) Process sequence of simulation

*Inherent strain calibration* involves evaluating cantilever beam deformation by initially setting the strain scaling factor to 1, then calibrating it based on the beam's experimental distortion until the simulation distortion matches the

experimental distortion and yields the corresponding SSF. Distortion at the red point in Figure 3 (a) is studied after support removal only. SSF value is calibrated to obtain the inherent strain by employing Equation 1.

In the IS simulation of the cantilever beam, only structural analysis is involved. The analysis is divided into three steps: building, support removal and base removal. In the build step, the part is built layer-wise with inherent strain applied; in the support removal step, the supports are deactivated in the model using the EKILL APDL command. Finally, the base is removed, as illustrated in Figure 3 (c).

## 3) Thermal Shrinkage Strain

In the thermal shrinkage method, inherent strain is evaluated by multiplying the equivalent thermal expansion coefficient (at room temperature) with the temperature difference (melting and room temperature), as given by formula [12]. The isotropic thermal shrinkage model is adopted for the current study.

$$\varepsilon = \alpha \cdot (T_m - T_a) \quad (11)$$

where  $T_m$  is the Ti6Al4V melting temperature (1605 °C), and  $T_a$  is the ambient temperature (25 °C).

## 3) Thermal Shrinkage Strain

Isotropic inherent strain is evaluated by taking the ratio of yield strength to Young's modulus (E) at room temperature, as shown in the formula.

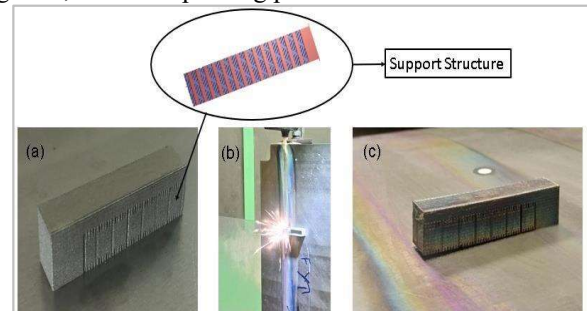
$$\varepsilon_{\text{isotropic}} = \frac{\sigma_y}{E} \quad (12)$$

## Detail of the Experiment

Ti6Al4V alloy powder is used for experimentation purposes, characterized by its spherical morphology. This titanium alloy has several advantages, including low density and a high strength-to-density ratio. The average particle size is around 30  $\mu\text{m}$ . To mitigate oxidation during the building process, the building chamber is filled with inert argon gas, maintaining oxygen levels below 300 ppm.

## 1) Experiment

The cantilever beam and support structure are printed using a Farsoon FS421-M SLM printer. Moreover, thin block supports are added along with solid supports, as shown in Figure 4, to aid the printing process.



**Figure 4:** Cantilever beam calibration specimen (a) Before support cutoff (b) wire EDM removal of supports (c) Distorted specimen after support cutoff.

After printing and cooling down, supports were removed from the base plate using wire EDM. After cutting the support structure from the base plate, the cantilever beam tip deflected

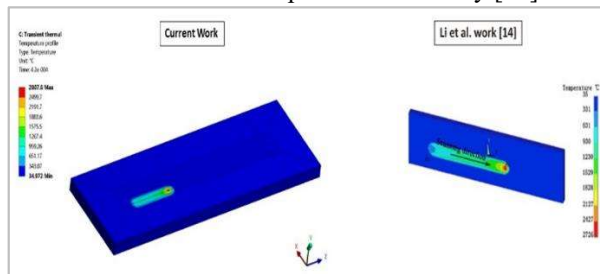
upward due to the buildup of residual stress in the part. The tip distortion was measured using 3D laser scanning to obtain precise results.

## Result and Discussion

This section details the results from simulation and experimental studies.

### 1) Meso-scale simulation

In the meso-scale simulation, laser heat sources, modeled as Gaussian heat flux in this study, scan three tracks on a single powder-bed layer. The powder is changed to bulk (liquid  $\rightarrow$  solid) when the laser beam scans the elements. The meso-scale simulation model is inspired by a study that employed Gaussian heat flux for meso-scale simulation [14]. Following a similar model and process parameters, the observed temperature profile oscillated between 2770–2988 °C, while the study reports 2732 °C, showing close agreement between the simulation and the literature. The laser absorptivity, not explicitly mentioned in the study, is taken to be 0.2 [20]. Moreover, severe transients are observed at the start of the third track. Overall, the thermal model is calibrated with  $\sim 10\%$  overall variation owing to the non-application of the simultaneous convection boundary condition along with the heat flux load, as the simultaneous application of convection and heat flux on the same surface is not supported, even for Surf 152 elements that are reported in the study [14].



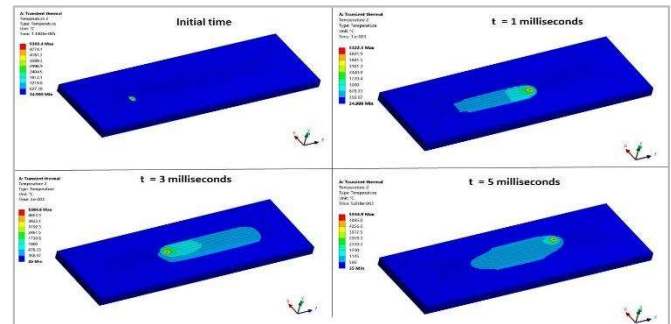
**Figure 5:** Comparison of temperature profile in meso-scale simulation

Moreover, since the mesh used is directly adopted from the work, i.e.,  $25 \times 25 \times 10 \mu\text{m}$ , the results are presumed to be mesh independent.

Still, results with a finer mesh of  $12.5 \times 12.5 \times 10 \mu\text{m}$  were  $\sim 2920$  °C (Peak Temperature), which also confirmed the hypothesis that the former mesh was adequate to capture the temperature accurately.

### Temperature profile evolution

After calibrating the thermal model, we used the process parameters in Table 1 for meso-scale simulation. For the print parameters used in this work, the input energy density is 4 times that used in the previous model calibration work [14]. Therefore, when the element temperature passes the ( $\alpha$  -  $\beta$ ) transition phase for Ti6Al4V, material properties change from powder to liquid.

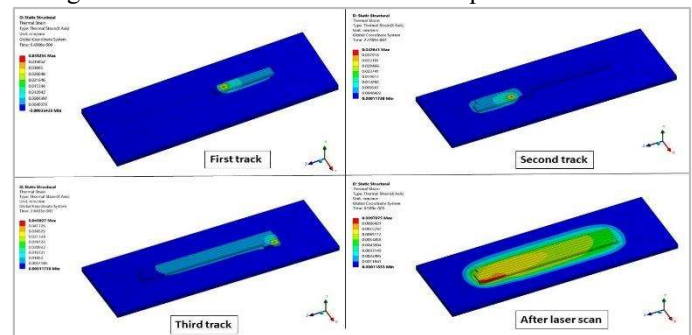


**Figure 6:** Evolution of temperature profile with time

It requires 5.4 milliseconds to complete three laser tracks, i.e., 1.8 milliseconds per track. The temperature increases from 5322 °C during the first track to 5384 °C during the second track and 5534 °C during the third track. The temperature transients arise from the problem's non-linearity, i.e., phase change, highly localized time, and space-dependent energy input. The extremely high temperature can be attributed to extreme laser parameters such as high power and low speed used in the current work.

### Structural Analysis

After the single-layer multi-track thermal analysis, the temperature is input into a structural module, where quasi-static analysis is performed. The typical element birth-and-death technique is employed, in which elements are born one after another under the input thermal load, as shown in Figure 7: Thermal strain contour plots showing quasi-static analysis through the element birth and death technique.

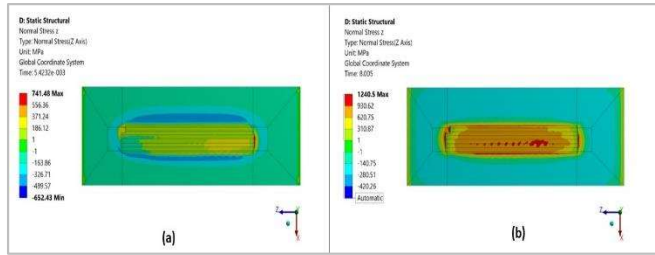


**Figure 7:** Thermal strain contour plots showing quasi-static analysis through element birth and death technique

### Stress Analysis

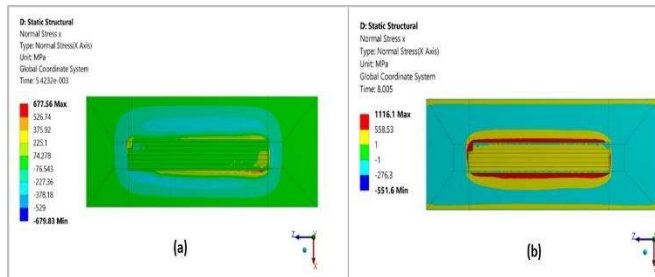
Analyzing normal stress behavior in meso-scale simulation is important for evaluating model behavior [3]. As previous studies predict, stresses are highest in the laser-scan direction. Figure 8 compares the laser-scan-direction (z-direction) normal stresses just after the laser scan and after complete cooldown. Just after the laser scan, maximum normal stress occurs near the scan region, inducing compressive stress in the nearby (blue-shaded) region because the substrate restrains thermal expansion. After complete cooldown, the deposited material shrinks, inducing compressive stresses at the corners of the deposition model. Moreover, the substrate region experiences high tensile stresses near the deposited

material. Another important point is the significant increase in tensile residual stresses after complete cooldown. The reasoning in this work is also supported by research by H. H. Shih [3].



**Figure 8:** Normal stress profile in laser scan direction (a) just after laser scan (b) after complete cooldown

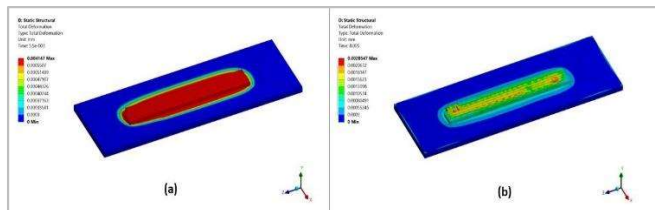
The normal stress profile across the laser scan direction ( $x$  direction), although not as significant, is shown in Figure 9. On deposited material, just after the laser scan, both tensile and compressive stresses of low magnitude are observed. Similarly, after cooldown, stresses in the vicinity of the deposited material, i.e., on the substrates, are high tensile residual stresses.



**Figure 9:** Normal stress across the laser scan direction (a) after laser scanning (b) after complete cooldown

### Deformation Study

The deformation contour plots reveal information about the expansion and contraction phenomena happening. Figure 10 shows that just after laser scanning, total deformation ( $4.55 \mu\text{m}$ ) is much greater than after complete cooldown ( $2.85 \mu\text{m}$ ). Moreover,  $y$ -direction deformation, i.e., the direction perpendicular to the plate, is a major contributor, such that other directional deformations can be safely neglected.

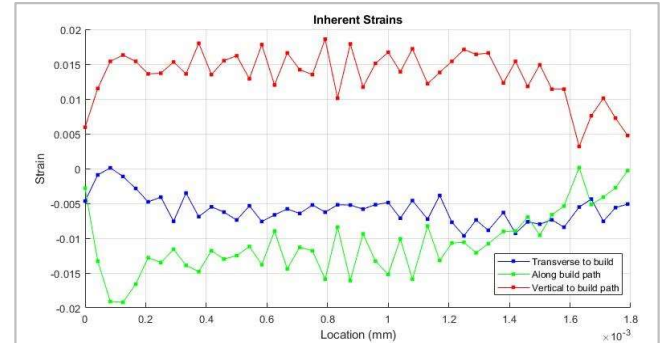


**Figure 10:** Deformation evolution (a) after laser scan (b) after cooldown

### Inherent strains evaluation

This study evaluates three inherent strains:  $\epsilon_{xx}$ ,  $\epsilon_{yy}$ , and  $\epsilon_{zz}$ . The relevant plastic and elastic strains at the intermediate state ( $t=5.4 \text{ ms}$ ) and after complete cooldown ( $t=8.005 \text{ s}$ ) are

extracted from the model at an inward depth of  $10 \mu\text{m}$  on the deposited material. This accounts for shrinkage after depositing another layer [15]. The inherent strains are obtained using the equation 10 and Figure 11, which shows the plot of three strains as a function of the middle scan path.

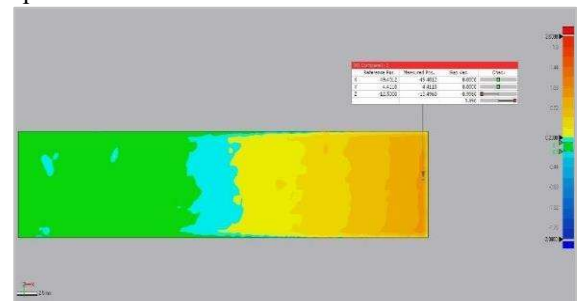


**Figure 11:** Three inherent strains from meso-scale simulation.

The qualitative sense of the inherent strain results obtained from meso-scale simulation is validated by an existing study by Q. Chen, in which different materials, process parameters, and a different heat source model are used. However, because the physics of meso-scale simulation is similar, the results of the present work are qualitatively comparable [15]. The inherent strains  $\epsilon_{xx}$ ,  $\epsilon_{yy}$ ,  $\epsilon_{zz}$  are  $-0.005$ ,  $-0.01$ ,  $0.015$ , respectively.

### 2) Experimentally Calibrated Inherent Strains

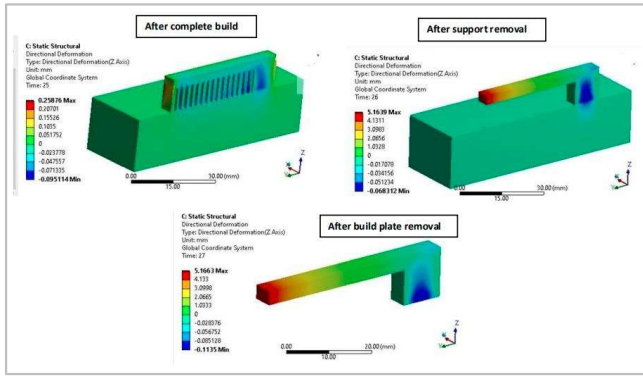
The cantilever beam deflection is measured using a laser scanner, followed by post-processing after support cutoff. Figure 12 depicts the color-mapped cantilever beam after laser scanning; it shows the deformation in the  $Z$  direction after the build and after support structure removal from the base plate.



**Figure 12:** Top view of color-mapped cantilever beam

### Calibration of inherent Strain (IS) analysis

The simulation shown in Figure 13 mimics the experiment; it shows distortion at the tip after build, support and base removal. The distortion of concern in the current study is the tip distortion after support removal, which was  $5.0376 \text{ mm}$ .



**Figure 13:** Cantilever beam deformation in the Z direction. Iterative calibration of FEM analyses is performed using experimental results. Calibration is done by first assuming SSF equals 1, then dividing the experimental distortion by the simulation-predicted distortion and multiplying by the SSF used in the simulation, vide Equation 1. Repeat this process until the simulation and experimental distortion values match. Table 3 tabulates the inherent-strain simulation calibration.

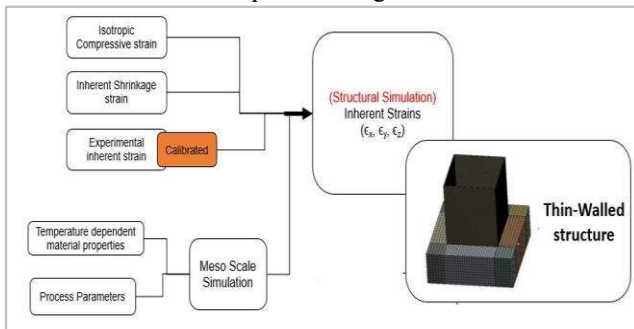
**Table 3:** Inherent strain iterative calibration

| IS SSF Calibration | Iteration | Direction | Distortion (mm) | Simulation settings | New Simulation settings | Error % |
|--------------------|-----------|-----------|-----------------|---------------------|-------------------------|---------|
|                    |           |           |                 | SSF                 | SSF                     |         |
|                    | 1st       | rotating  | 5.0376          | 1.000               | 0.198                   | 80.2    |
|                    | 2nd       |           | 1.2489          | 0.198               | 0.158                   | 18.5    |
|                    | 3rd       |           | 0.99865         | 0.158               | 0.157                   | 0.63    |

\* Error (%) represents the percentage change in the Inherent Strain Scale Factor (SSF) between successive iterations, calculated as  $|\text{SSF}(\text{updated}) - \text{SSF}(\text{previous})| / \text{SSF}(\text{previous}) \times 100$ .

### 3) Part Scale Comparative Simulations Study

The goal of the study is to compare various part-scale SLM simulation methodologies widely adopted in literature or offered by SLM simulation software, especially for thin-walled structures, as depicted in Figure 14.



**Figure 14:** Simulation methodology used in present study

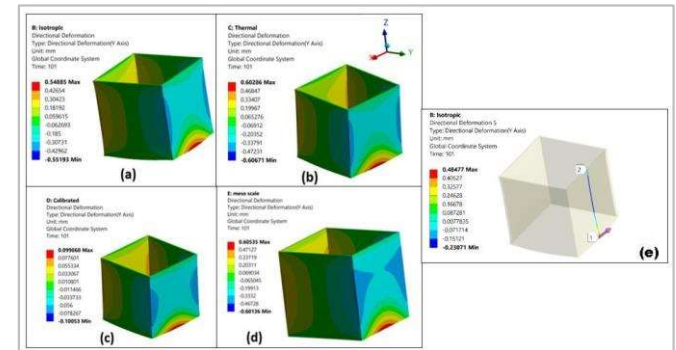
The inherent strains, whether isotropic or anisotropic (meso-scale simulation), are applied as strain scaling factors SSF. For isotropic compressive strain SSF of unity is applied; for inherent shrinkage strain SSF of 1.4 is applied. The calibrated SSF for inherent strain simulation is 0.18, and meso-scale-based anisotropic strains are derived from the previous section. The deformation analysis for single-wall, square and

cylindrical thin-walled structures with a 1 mm thickness, after building platform removal, is elaborated subsequently.

**Table 4:** Four different inherent strain methods for SLM part-level simulation

| Input parameter                           | Value             |
|-------------------------------------------|-------------------|
| Isotropic compressive yield strain (IS)   | $\sigma_y / E$    |
| Thermal Shrinkage strain (IS)             | $\alpha \Delta T$ |
| Experimentally determined inherent strain | Experimental      |
| Meso-scale simulation (IS)                | Simulation        |

*Square Thin-walled structures:* Analysis of the square thin-walled structure depicted inward bulging when the base plate is removed after layer-by-layer deposition of the part. Figure 15 compares y-direction deformations for four different simulation strategies. It should be noted that deformations predicted by isotropic, thermal and meso-scale strain-based structural analysis (a), (b) and (d) are similar, while the experimentally calibrated structural analysis (c) presented a similar distortion qualitatively but of very little magnitude compared to the others. A similar phenomenon is observed for x-directed distortion, except for the meso-scale simulation, where the maximum x distortion was  $\sim 0.2$  mm. The z deformation for every case was maximum on the edges of square.

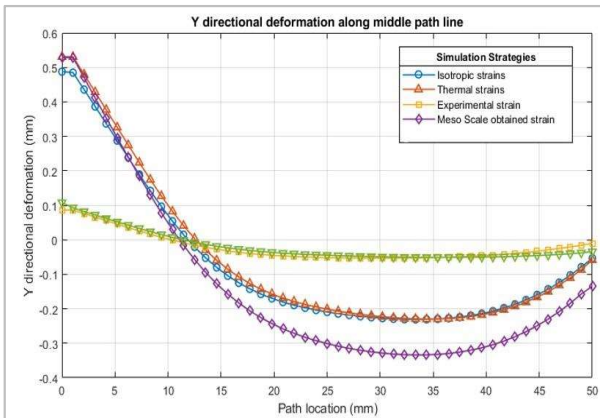


**Figure 15:** Y-directional deformation in square wall (a) Isotropic Strain (b) Inherent shrinkage strain (c) Experimentally calibrated inherent strain (d) meso-scale-based strains (e) Middle path line for comparative distortion study

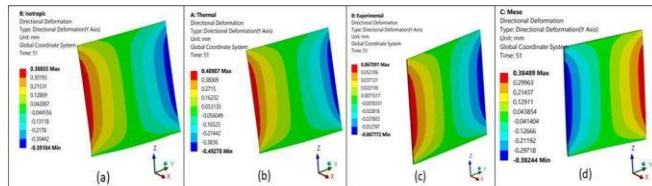
Figure 16 shows the comparative plot of deformation variation for various simulation strategies.

*Single Walled Structures:* Analysis of a single thin-walled structure  $1 \times 100 \times 100$  mm is carried out; the Y-direction deformations are compared for four different simulation strategies, as shown in Figure 17. It should be noted that deformations predicted by isotropic, thermal and meso-scale strain-based structural analysis (a), (b) and (d) are nearly similar, while the experimentally calibrated structural analysis (c) presented almost similar distortion qualitatively. Moreover, qualitative predictions from all simulation types

are similar in every direction except the meso-scale simulation.

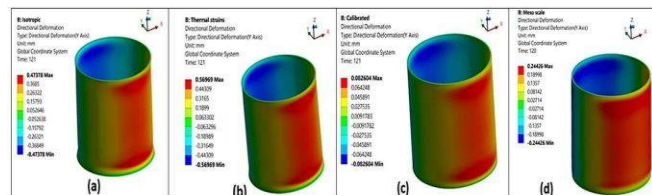


**Figure 16:** Comparative plot showing variation of y-directional deformation along vertical path for five simulation strategies.



**Figure 17:** Y-directional deformation in single wall structure

*Cylindrical Thin-walled structures:* Analysis of the cylindrical thin-walled structure depicted inward bulging. The y-direction deformations, when compared for four different simulation strategies as shown in Figure 18, revealed that deformations predicted by isotropic, thermal and meso-scale strain-based structural analysis (a), (b) and (d) are similar, while the experimentally calibrated structural analysis (c) presented a similar distortion qualitatively but with significantly less magnitude. A similar phenomenon is observed for x-directed distortion, except in the meso-scale simulation.

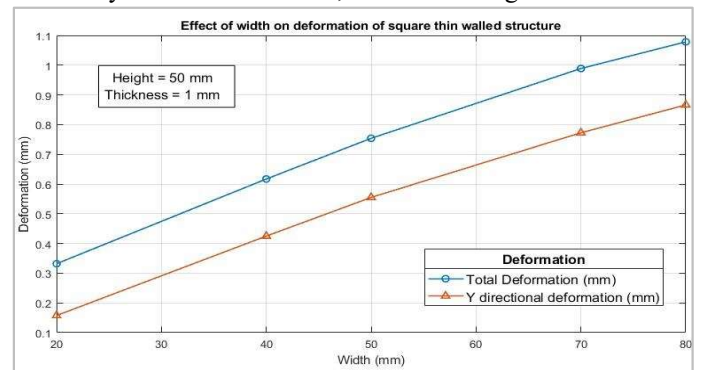


**Figure 18:** Y-directional deformation in thin cylindrical wall structure

#### 4) Parametric Analysis of Thin-Walled Structures

The parametric analysis in this section focuses on how varying width/diameter, height, and thickness affects single-wall, square-wall, and cylindrical structures. The section below describes the observed effects sequentially: first for square, then for cylindrical and finally for single-wall structures.

*Square-walled structure:* In the first study, a square structure with a 1 mm wall thickness was subjected to a Design of Experiments (DOE) to investigate how varying height and width affected its mechanical behavior. The design parameters were the square structure's height and width, and the responses were total deformation and Y-directional deformation, measured in millimeters. The study explored how changes in the square structure's dimensions affect its deformation characteristics. The DOE results show that variations in both height and width significantly affect the square structure's deformation behavior. For instance, increasing the height while keeping the width constant changes both total deformation and Y-directional deformation. Similarly, changing the width at a fixed height noticeably affects deformation, as shown in Figure 19.

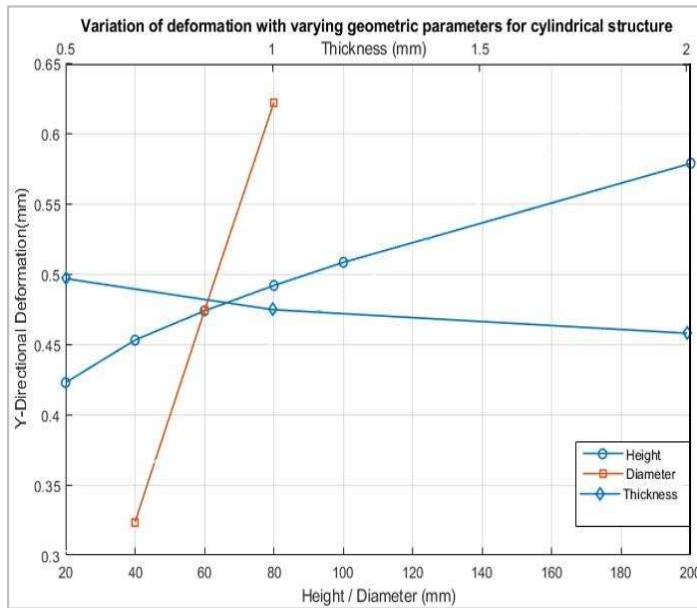


**Figure 19:** Effect of width on deformation of square structures

Varying Height from 40 to 200 mm at a wall thickness of 1 mm and a width of 50 mm showed negligible variation in deformations. Moreover, the sharp corners of the square structure experienced the maximum total deformation and developed directional normal stress. Thus, sharp-cornered structures, especially for SLM, should be avoided or rounded and bulged with more material to improve heat-transfer performance and structural stiffness at sharp corners.

*Cylindrical structure:* The effect of three independent parameters for the cylindrical structure, i.e., outer diameter, height and wall thickness, is parametrically studied. Figure 20 shows that distortion in the cylindrical shape depends strongly on diameter, followed by height and thickness. Increasing height or diameter depicted increased distortion, while increasing thickness up to 2 mm depicted a slight decrease in distortion of the cylindrical structure, as anticipated.

*Single-walled structure:* The effect of three independent parameters for the single-walled structure, i.e., width, height and wall thickness, was parametrically studied. Distortion in the single-walled structure was found to be strongly dependent on wall width. The dependence of distortion on thickness (0.5-2 mm) and height is not appreciable as compared to width.



**Figure 20:** Effect of geometric parameters on cylinder distortion

## Conclusion

This work mainly focused on predicting distortion before SLM printing thin-walled components. This work compares various simulation strategies commonly used in the literature for part-level SLM simulation of thin-walled structures. The study analyzes the effect of variations in geometric parameters for thin-walled square, cylindrical, and single-walled structures. Predicted distortion for square, cylindrical, and single walled structure using 4 different simulation strategies, i.e., Isotropic yield strain, thermal shrinkage strain, experimental strain, meso scale obtained strains, yielded qualitatively similar distortions, with differences in magnitude, especially for the experimentally calibrated simulation technique. Moreover, the isotropic yield strain method is suitable for qualitative distortion profiles of symmetric thin-walled structures like single-walled, square, and cylindrical ones and is also suitable for comparative studies with regards to part-level simulation of thin-walled structures. Square-walled thin structures exhibited high stress and distortion at sharp corners. Moreover, out of three geometric parameters like width, height and thickness of the square wall, width strongly influences distortion and increasing width increased distortion almost linearly. Cylindrical thin-walled structures exhibited low deformation as compared to the square section. Increasing diameter and height depicted increased distortion, while increasing thickness from 0.5 to 2 mm showed a slight decrease in distortion. For single-walled structures, wall width strongly affects distortion compared with the other two geometric parameters. It can be safely concluded that, generally, the width of a thin-walled section has a strong relationship with distortion, and increasing width increases distortion for thin-walled sections. The complex thermo-mechanics of SLM-

manufactured parts need not be simulated for part-level analysis; structural analysis alone (preferably with a calibration process) can provide accurate part-level simulated results. Moreover, when distortion magnitude is not the primary concern, only the distortion profile and areas of expected high deformation are required; isotropic yield strain values are enough for an accurate qualitative distortion overview.

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